INDIAN AGRICULTURAL
RESEARCH INSTITUTE, NEW DELHI.

I. A. R. I. 6.
MGIPC—S1—6 AR/54—7-7-54—10,000.

46483

ENCYCLOPEDIA OF CHEMICAL TECHNOLOGY

VOLUME 14

ENCYCLOPEDIA OF CHEMICAL TECHNOLOGY

Edited by RAYMOND E. KIRK
Head, Department of Chemistry, Polytechnic Institute of Brooklyn
and DONALD F. OTHMER
Head, Department of Chemical Engineering, Polytechnic Institute of Brooklyn

46483
IARI

Assistant Editors
JANET D. SCOTT *and* ANTHONY STANDEN

VOLUME 14

THERMODYNAMICS
to
WATERPROOFING

46483

THE INTERSCIENCE ENCYCLOPEDIA, INC. NEW YORK

Copyright 1955, by
THE INTERSCIENCE ENCYCLOPEDIA, INC.

All Rights Reserved

This book or any part thereof must not be reproduced in any form without permission of the publishers in writing. This applies specifically to photostatic and microfilm reproductions.

Distributed by
INTERSCIENCE PUBLISHERS, INC.
250 Fifth Avenue, New York 1, N. Y.

Printed in U.S.A. by
Mack Printing Co., Easton, Pa.

EDITORIAL STAFF FOR VOLUME 14

Janet D. Scott **Anthony Standen**

Alberta L. Kelvie **James A. Lecky** **Annette Stern**

CONTRIBUTORS TO VOLUME 14

Claude H. Alexander, B. F. Goodrich Chemical Company, *Vinyl compounds (vinyl chloride)*

D. E. Badertscher, Socony Mobil Oil Co., Inc., *Thiophene*

H. H. Beacham, Titanium Division, National Lead Company, *Titanium compounds*

R. L. Bent, Eastman Kodak Company, *Valence*

Jack Bernstein, The Squibb Institute for Medical Research, *Tuberculostatic agents*

G. L. Beyer, Eastman Kodak Company, *Turbidimetry and nephelometry*

K. G. Blaikie, Shawinigan Chemicals Limited, "Polyvinyl acetate solid resins" and "Polyvinyl acetate emulsions" under *Vinyl compounds (vinyl acetate)*; *Vinyl compounds (polyvinyl acetals)*

L. R. Blair, Titanium Division, National Lead Company, *Titanium compounds*

Robert Calvert, Patent Attorney, *Trade-marks*

Ju Chin Chu, Polytechnic Institute of Brooklyn, *Thermodynamics*

A. J. Cofrancesco, General Aniline & Film Corporation, *Triphenylmethane and diphenylnaphthylmethane dyes*

Gerard F. Cohan, B. F. Goodrich Chemical Company, *Vinyl compounds (vinyl chloride)*

C. M. Cosman, Vanadium Corporation of America, *Vanadium compounds*

W E Craig, Rohm & Haas Company, *Thiocyanates and isothiocyanates, organic*

E. J. Crane, "Chemical Abstracts," *Units and their symbols*

T. W. Davis, New York University, *Water*

B. B. Dayton, Consolidated Vacuum Corporation, *Vacuum technique*

H. E. Dunn, Vanadium Corporation of America, *Vanadium compounds*

Norris D. Embree, Distillation Products Industries, Division of Eastman Kodak Company, *Vitamins (vitamin E)*

J. V. Festa, Sylvania Electric Products, Inc., *Vacuum tubes*

Lamar Field, Vanderbilt University, *Thio acids*

John Figueras, Jr., Eastman Kodak Company, *Valence*

C. E. Funk, Jr., Research Division, American Cyanamid Company, *Urea (derivatives)*

J. A. Garman, Fairfield Chemical Division, Food Machinery and Chemical Corporation, *Urethans*

E. A. Gee, E. I. du Pont de Nemours & Co., Inc., Pigments Department, *Titanium and titanium alloys*

L. M. Germain, Shawinigan Chemicals Limited, *Vinyl compounds (polyvinyl alcohol)*

S. D. Gershon, Lever Brothers Company, *Thioglycolic acid*

Roger Gilmont, The Emil Greiner Co., *Vapor–liquid equilibria and vapor pressure*

Margot Goehring, University of Heidelberg, *Thionic acids*

D. R. Gray, The Dow Chemical Company, *Vinyl compounds (vinylidine chloride)*

H. O. Halvorson, University of Illinois, *Water (municipal)*

W. R. Harlan, The American Tobacco Company, *Tobacco*

Philip L. Harris, Distillation Products Industries, Division of Eastman Kodak Company, *Vitamins (vitamin E)*

Ralph F. Hirschmann, Merck & Co., Inc., *Vitamins (vitamin K)*

Frank Hovorka, Western Reserve University, *Ultrasonics*

E. M. Jenkins, Johns-Manville Research Center, *Wallboard* (in part)

R. G. Jones, Eli Lilly and Company, "Antithyroid substances" under *Thyroid and antithyroid preparations*

M. A. Joslyn, University of California, *Vinegar*

J. J. Katz, Argonne National Laboratory, *Uranium and uranium compounds*

Stuart D. Kerr, Cincinnati Chemical Works, Inc., *Thiazole dyes*

Bernard Kopelman, Sylvania Electric Products, Inc., *Tungsten and tungsten alloys*; *Tungsten compounds*

H. E. Kremers, Lindsay Chemical Company, *Thorium and thorium compounds*

Maury Lapeyrouse, Esso Research and Engineering Company, *Toluene*

J. B. Lesh, The Armour Laboratories, "Thyroid preparations" under *Thyroid and antithyroid preparations*

Sidney B. Levinson, D. H. Litter Co., Inc., *Varnishes*

R. M. MacIntosh, Tin Research Institute, Inc., *Tin and tin alloys*

S. B. Mecca, Schuylkill Chemical Company, *Uric acid*

Shirley K. Morse, General Aniline & Film Corporation, "Dye intermediates" under *Toluenesulfonic acids*

J. M. Moseley, The American Tobacco Company, *Tobacco*

T. E. Neesby, Carroll Dunham Smith Pharmacal Company, "Applications" under *Thionic acids*

R. J. Nekervis, Tin Research Institute, Inc., *Tin and tin alloys*

W. K. Nelson, Titanium Division, National Lead Company, *Titanium compounds*

D. J. O'Flynn, E. I. du Pont de Nemours & Co., Inc., Polychemicals Department, *Urea*

H. E. Orford, Rutgers University, *Wastes, industrial*

William Oroshnik, Ortho Research Foundation, *Vitamins (vitamin A)*

Donald F. Othmer, Polytechnic Institute of Brooklyn, *Vapor–liquid equilibria and vapor pressure*

W. A. Parsons, Rutgers University, *Wastes, industrial*

Everett P. Partridge, Hall Laboratories, Inc., *Water (industrial)*

Earl Pierson, Merck & Co., Inc., *Thiamine*

P. E. Porter, Shell Development Company, *Viscometry*

R. W. Radue, Monsanto Chemical Company, *Toluenesulfonic acids and toluenesulfonyl chlorides*

D. I. Randall, General Aniline & Film Corporation, *Vat dyes*

H. E. Rasmussen, Socony Mobil Oil Co., Inc., *Thiophene*

Martha T. Rathgeb, Cincinnati Chemical Works, Inc., *Thiazole dyes*

J. David Reid, Southern Utilization Research Branch, Agricultural Research Service, U.S. Department of Agriculture, *Waterproofing and water repellency*

Desmond M. C. Reilly, Food Machinery and Chemical Corporation (Chemical Divisions), *Vanillin*

L. G. Ricciardi, Polytechnic Institute of Brooklyn, *Wallboard* (in part)

Hartmut Richter, Metal & Thermit Corporation, *Tin compounds*

M. M. Rieger, Lever Brothers Company, *Thioglycolic acid*

F. M. Robinson, Merck & Co., Inc., *Vitamins (vitamin B_{12})*

H. R. Rosenberg, E. I. du Pont de Nemours & Co., Inc., Grasselli Chemicals Department, *Vitamins (survey; vitamin D)*

T. P. G. Shaw, Shawinigan Chemicals Limited, "Vinyl acetate monomer" and "Polyvinyl acetate solid resins" under *Vinyl compounds (vinyl acetate)*; *Vinyl compounds (polyvinyl alcohol)*

R. Norris Shreve, Purdue University, *Unit operations and unit processes*

M. S. W. Small, Shawinigan Chemicals Limited, "Polyvinyl acetate emulsions" under *Vinyl compounds (vinyl acetate)*; *Vinyl compounds (polyvinyl acetals)*

W. B. Snow, Rutgers University, *Wastes, industrial*

E. A. Steck, Sterling-Winthrop Research Institute, *Trypanocides*

W. D. Stonecipher, Hercules Powder Company, *Turpentine*

Jerome Strauss, Vanadium Corporation of America, *Vanadium and vanadium alloys*

F. H. Stross, Shell Development Company, *Viscometry*

L. E. Swanson, The Vulcan Detinning Company, *Tin and tin alloys (detinning)*

R. H. Taylor, The Vulcan Detinning Company, *Tin and tin alloys (detinning)*

R. V. Townend, General Chemical Division, Allied Chemical & Dye Corporation, *Thiosulfuric acid and thiosulfates*

J. O. Van Hook, Rohm & Haas Company, *Thiocyanates and isothiocyanates, organic*

Florence E. Wall, Consulting Chemist, *Tints, hair dyes and bleaches*

Mollie G. Weller, E. I. du Pont de Nemours & Co., Inc., Grasselli Chemicals Department, *Vitamins (survey)*

J. Homer Winkler, Battelle Memorial Institute, *Type metals and plate materials*

C. H. Winter, Jr., E. I. du Pont de Nemours & Co., Inc., Pigments Department, *Titanium and titanium alloys*

D. M. Wolfe, Lederle Laboratories Division, American Cyanamid Company, *Vaccines*

F. A. Wolff, E. I. du Pont de Nemours & Co., Inc., Polychemicals Department, *Urea*

Ruby K. Worner, Southern Utilization Research Branch, Agricultural Research Service, U.S. Department of Agriculture, *Waterproofing and water repellency*

Ernest Yeager, Western Reserve University, *Ultrasonics*

ABBREVIATIONS AND SYMBOLS

A.	Ångström unit(s)
A	anion; as, H*A*
abs.	absolute
a.c.	alternating current
ac-	alicyclic; as, *ac*-derivatives of tetrahydronaphthalene
A.C.S.	American Chemical Society
addn.	addition
A.G.A.	American Gas Association
A.I.Ch.E.	American Institute of Chemical Engineers
A.I.M.E.	American Institute of Mining and Metallurgical Engineers
alc.	alcohol, alcoholic
alk.	alkaline (not alkali)
Alk	alkyl
amp.	ampere(s)
amp.-hr.	ampere-hour(s)
amt.	amount (noun)
anhyd.	anhydrous
A.P.I.	American Petroleum Institute
app.	apparatus
approx.	approximate (adj.), approximately
aq.	aqueous
Ar	aryl
ar-	aromatic; as, *ar*-derivatives of tetrahydronaphthalene
as-	asymmetric; as, *as-m*-xylidine
ASA	American Standards Association
A.S.M.	American Society for Metals
A.S.M.E.	American Society of Mechanical Engineers
A.S.T.M.	American Society for Testing Materials
atm.	atmosphere(s), atmospheric
at. no.	atomic number
at. wt.	atomic weight
av.	average
b. (as, b_{11})	boiling (at 11 mm.)
B	base; as, *B*.2HCl
bbl.	barrel(s)
Bé.	Baumé
b.p.	boiling point
B.t.u.	British thermal unit(s)
bu.	bushel(s)
C.	centigrade
C-	denoting attachment to carbon; as, *C*-alkyl derivatives of aniline
cal.	calorie(s)
calcd.	calculated
c.f.m.	cubic foot (feet) per minute
cg.	centigram(s)
c.g.s.	centimeter-gram-second
chem.	chemical
C.I.	*Colour Index* no.
cks.	centistokes
c.l.	car lots
cm.	centimeter(s)
coeff.	coefficient
com.	commercial
compd.	compound (noun)
compn.	composition
concd.	concentrated
concn.	concentration
cond.	conductivity
const.	constant
cor.	corrected

c.p.	chemically pure
cps.	centipoise
crit.	critical
cryst.	crystalline
crystd.	crystallized
crystn.	crystallization
cu.	cubic
d (as, d_4^{20})	density (conveniently, specific gravity)
d	differential operator
d-	*dextro-*, dextrorotatory
D-	denoting configurational relationship, as to *dextro*-glyceraldehyde
d.c.	direct current
dec., decomp.	decompose(s)
decompn.	decomposition
deriv.	derivative
detd.	determined
detn.	determination
diam.	diameter
dielec.	dielectric (adj.)
dil.	dilute
dist.	distilled
distn.	distillation
DL-, *dl-*	racemic
dm.	decimeter
e	electron
ed.	edition, editor
elec.	electric, electrical
elev.	elevated
e.m.f.	electromotive force
eng.	engineering
eq.	equation
equil.	equilibrium
equiv.	equivalent
esp.	especially
estd.	estimated
estn.	estimation
e.s.u.	electrostatic unit(s)
e.u.	entropy unit(s)
e.v.	electron volt(s)
expt.	experiment
exptl.	experimental
ext.	extract
extd.	extracted
extn.	extraction
F.	Fahrenheit
Fedl.	Federal
ff.	following (pages)
fl.oz.	fluid ounce(s)
f.o.b.	free on board
f.p.	freezing point
ft.	foot (feet)
ft.-lb.	foot-pound(s)
g.	gram(s)
gal.	gallon(s)
g.p.d.	grams per denier
g.p.m.	gallons per minute
hp.	horsepower
hr.	hour(s)
hyd.	hydrated, hydrous
i.	insoluble
i-	inactive; as, *i*-methionine
i.b.p.	initial boiling point
I.C.C.	Interstate Commerce Commission
I.D.	inner diameter
in.	inch(es)
insol.	insoluble
I.P.T.	Institute of Petroleum Technologists
I.U.	International Unit(s)
I.U.C., I.U.P.A.C.	International Union of Chemistry, International Union of Pure and Applied Chemistry
j.	joule
K.	Kelvin
K	dissociation constant
Kev	kilo electron volt
kg.	kilogram(s)
kg.-cal.	kilogram-calorie(s)
kv.	kilovolt(s)
kv.-amp.	kilovolt-ampere(s)
kw.	kilowatt(s)
kw.-hr.	kilowatt-hour(s)
l.	liter(s)
l-	*levo-*, levorotatory
L-	denoting configurational relationship, as to *levo*-glyceraldehyde
lb.	pound(s)
LC_{50}	concentration lethal to 50% of animals tested

l.c.l.	less than car lots
LD_{50}	dose lethal to 50% of animals tested
ln	logarithm (natural)
log	logarithm (common)
m.	meter(s)
m-	meta; as, *m*-xylene
M	metal
M	molar (as applied to concn.; not molal, which is written out)
ma.	milliampere(s)
manuf.	manufacture
manufd.	manufactured
manufg.	manufacturing
max.	maximum
M.C.A.	Manufacturing Chemists' Association
m.c.f.	million cubic feet
m.e., meq.	milliequivalent(s)
mech.	mechanical
M.e.v.	million electron volts
mg.	milligram(s)
m.g.d.	million gallons per day
min.	minimum; minute(s)
misc.	miscellaneous
mixt.	mixture
ml.	milliliter(s)
M.L.D.	minimum lethal dose
mm.	millimeter(s)
mM	millimole(s)
mol.	molecule, molecular
m.p.	melting point
m.p.h.	miles per hour
M.R.	molar refraction
mv.	millivolt(s)
$m\mu$	millimicron(s)
n (as, n_D^{20})	index of refraction (for 20°C., and sodium light)
n-	normal; as, *n*-butyl
N	normal (as applied to concn.)
N-	denoting attachment to nitrogen; as, *N*-methylaniline
neg.	negative (adj.)
no.	number
N.O.I.B.N.	not otherwise indexed by name
o-	ortho; as, *o*-xylene
O-	denoting attachment to oxygen; as, *O*-acetylhydroxylamine
O.D.	outer diameter
oz.	ounce(s)
p., pp.	page, pages
p-	para; as, *p*-xylene
pos.	positive (adj.)
powd.	powdered
p.p.m.	parts per million
ppt.	precipitate
pptd.	precipitated
pptn.	precipitation
prepd.	prepared
prepn.	preparation
Pr. no.	Foreign Prototype no. (for dyes)
p.s.i.(g.),(a.)	pound(s) per square inch (gage), (absolute)
pt.	point
pts.	parts
quad. pt.	quadruple point
qual.	qualitative
quant.	quantitative
q.v.	"which see"
R	univalent hydrocarbon radical (or hydrogen)
R.	Rankine
ref.	reference
resp.	respectively
r.h.	relative humidity
R.I.	*Ring Index* no.
r.p.m.	revolutions per minute
r.p.s.	revolutions per second
s.	soluble
s-	symmetric(al); as, *s*-*m*-xylidine
S-	denoting attachment to sulfur; as, *S*-methylcysteine
S.A.E.	Society of Automotive Engineers
satd.	saturated
satn.	saturation

S.C.F.	standard cubic foot (feet)	t.s.i.	tons per square inch
Sch.	Schultz no. (for dyes)	Twad.	Twaddell
sec.	second(s)	u.v.	ultraviolet
sec-	secondary; as, *sec*-butyl	v.	volt(s)
S.F.s.	Saybolt Furol second(s)	var.	variety
sl.s.	slightly soluble	*vic-*	vicinal; as, *vic-m*-xylidine
sol.	soluble	vol.	volume(s) (not volatile)
soln.	solution	v.s.	very soluble
soly.	solubility	w.	watt(s)
sp.	specific	wt.	weight
sp., spp.	species	X.U. (10^{-10} mm.)	X-unit
spec.	specification	yd.	yard(s)
sp.gr.	specific gravity	yr.	year(s)
sq.	square	$[\alpha]_D^{20}$	optical rotation (for 20°C. and sodium light)
S.T.P.	standard temperature and pressure	γ	microgram(s)
subl.	sublime(s), subliming	∂	differential operator (partial)
S.U.s.	Saybolt Universal second(s)	Δ	finite difference
sym-	symmetric(al); as, *sym-m*-xylidine	η	viscosity
T.A.P.P.I.	Technical Association of the Pulp and Paper Industry	λ	wave length
		μ	micron(s)
tech.	technical	Ω	ohm(s)
temp.	temperature	$<$	less than
tert-	tertiary; as, *tert*-butyl	$>$	more than
theoret.	theoretical	$\sim$	cycle(s)
t.p.h.	tons per hour	$\lesssim$	approximately equal to

Other letter symbols may be found in "Standard System of Nomenclature for Chemical Engineering Unit Operations" adopted by the American Institute of Chemical Engineers.

SHIPPING REGULATIONS

Complete information for the U.S. is given in "Tariff No. 9 Publishing Interstate Commerce Commission Regulations for Transportation of Explosives and Other Dangerous Articles by Land and Water in Rail Freight Service and by Motor Vehicle (Highway) and Water Including Specifications for Shipping Containers," with supplements, issued by H. A. Campbell, Agent, 30 Vesey Street, New York 7, N.Y. (1954). The following terms for labeling explosives and other dangerous articles have been used in the Encyclopedia:

Red label (for inflammable liquids)
Yellow label (for inflammable solids and oxidizing materials)
White label (for acids and corrosive liquids)
Red label (for inflammable compressed gases)
Green label (for noninflammable compressed gases)
N.O.I.B.N. (not otherwise indexed by name)

In the text of the Encyclopedia the preferred terms "flammable" and "nonflammable" are used in place of "inflammable" and "noninflammable," respectively.

STANDARD REFERENCE WORKS

The titles of the following reference works have usually been abbreviated when they are given in the bibliographies. See also *Literature of chemical technology*, Vol. 8, p. 418.

Adams, R. (ed.), *Organic Reactions*, Wiley, N.Y., 8+ Vols., 1942–.

Allen, A. H., *Commercial Organic Analysis*, 5th ed., McGraw-Hill–Blakiston, New York, Vols. I–X, 1923–33.

American Association of Textile Chemists and Colorists (A.A.T.C.C.), *1954 Technical Manual and Year Book*, Howes Pub. Co., N.Y., 1954.

American Society for Testing Materials, *1952 Book of A.S.T.M. Standards*, Philadelphia, 7 Parts, 1952–53.

American Standards Association (ASA), *American Standards*, N.Y.

Annual Tables of Constants and Numerical Data, C. Marie (ed.), McGraw-Hill, N.Y., 1912–34.

Association of Official Agricultural Chemists (A.O.A.C.), *Official and Tentative Methods of Analysis of the Association of Official Agricultural Chemists*, 7th ed., Collegiate Press, Menasha, Wis., 1950.

Badger, W. L., and McCabe, W. L., *Elements of Chemical Engineering*, 2nd ed., McGraw-Hill, N.Y., 1936.

Beilstein, F. K., *Handbuch der organischen Chemie*, 4th ed., Springer, Berlin and Heidelberg, 71+ Vols., 1918–. (64 Vols. photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.)

Brauer, G. (ed.), *Handbuch der präparativen anorganischen Chemie*, Enke, Stuttgart.

Clark, B. L., and Kolthoff, I. M. (eds.), *Chemical Analysis*, Interscience, N.Y.-London, 7+ Vols., 1945–.

Cook, E. F., and Martin, E. W. (eds.), *Remington's Practice of Pharmacy*, 9th ed., Mack Pub. Co., Easton, Penna., 1948.

Elderfield, R. C. (ed.), *Heterocyclic Compounds*, Wiley, N.Y., 6 Vols., 1950–.

Faith, W. L., Keyes, D. B., and Clark, R. L., *Industrial Chemicals*, Wiley, N.Y., 1950.

Friedländer, P., *Fortschritte der Teerfarbenfabrikation und verwandter Industriczweige*, Springer, Berlin, Vols. I–XXV, 1888–1942.

Friend, J. N. (ed.), *Textbook of Inorganic Chemistry*, Griffin, London, Vols. I–XI, 1914–38.

Gmelins Handbuch der anorganischen Chemie, 8th ed., Verlag Chemie, Weinheim/Bergstrasse, System-Nummern 1–70, 1924–.

Great Britain General Medical Council, *British Pharmacopæia*, Constable, London, 1948; Addendum, 1951.

Handbook of Chemistry and Physics, C. D. Hodgman (ed.), 36th ed., Chem. Rubber Pub. Co., Cleveland, 1954.

Heilbron, I. M., and Bunbury, H. M., *Dictionary of Organic Compounds*, Oxford Univ. Press, N.Y., Vols. I–IV, new rev. ed., 1953.

Houben, J. (ed.), *Methoden der organischen Chemie* (*Weyls Methoden*), 3rd ed., Thieme, Leipzig, Vols. I–IV, 1925–41. (Photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.) For new edition see under Müller, E.

Houben, J., *Fortschritte der Heilstoffchemie*. Erste Abteilung: *Das deutsche Patentschriftwesen*, Vols. I–VI; Zweite Abteilung: *Die Ergebnisse der wissenschaftlichen Literatur*, Vols. I–III; de Gruyter, Berlin, 1926–39. (Photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.)

Huntress, E. H., *Organic Chlorine Compounds*, Wiley, N.Y., 1948.

Inorganic Syntheses, McGraw-Hill, N.Y., 4+ Vols., 1939–.

International Critical Tables of the Numerical Data of Physics, Chemistry, and Technology (I.C.T.), E. W. Washburn (ed.), McGraw-Hill, N.Y., Vols. I–VIII, 1926–33.

Landolt-Börnstein, *Physikalisch-chemische Tabellen*, 5th ed., Springer, Berlin, 8 Vols., 1923–36 (photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.); 6th ed., *Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik, Technik*, A. Eucken (ed.), Vols. I–IV, 1950–.

Lange, N. A., and Forker, G. M. (eds.), *Handbook of Chemistry*, 8th ed., Handbook Publishers, Sandusky, Ohio, 1952.

Lunge, G., and Berl, E., *Chemisch-technische Untersuchungsmethoden*, 8th ed., Springer, Berlin, 8 Vols., 1931–40. (Photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.)

Mark, H., Marvel, C. S., Melville, H. W., and Whitby, G. S. (eds.), *High Polymers*, Interscience, N.Y.-London, 9+ Vols., 1940–.

Mellor, J. W., *Comprehensive Treatise on Inorganic and Theoretical Chemistry*, Longmans, Green, N.Y., Vols. I–XVI, 1922–37.

Merck Index, The, 6th ed., Merck & Co., Inc., Rahway, N.J., 1952.

Müller, E. (ed.), *Methoden der organischen Chemie* (*Houben-Weyl*), 4th ed., Thieme, Stuttgart, approx. 12 Vols., 1952–.

National Formulary, The, 9th ed. (N.F. X), Committee on National Formulary, American Pharmaceutical Association, Washington, D.C., 1955.

New and Nonofficial Remedies—1954 (N.N.R.) (1954); *Tests and Standards for New and Nonofficial Remedies* (1953); Council on Pharmacy and Chemistry of the American Medical Association, Lippincott, Philadelphia.

Organic Syntheses, Wiley, N.Y., Collective Vol. I (Vols. I–IX), 2nd ed., 1941; Collective Vol. II (Vols. X–XIX), 1943; Collective Vol. III (Vols. XX–XXIX), 1955.

Osol, A., and Farrer, G. E., Jr., *et al.*, *The Dispensatory of the United States of America* (U.S.D.), 24th ed., Lippincott, Philadelphia, 1947; Supplement, 1950.

Palache, C., Berman, H., and Frondel, C., *Dana's System of Mineralogy*, 7th ed., Wiley, N.Y., 3 Vols., 1944–.

Patterson, A. M., and Capell, L. T., *The Ring Index* (*R.I.*), Reinhold, N.Y., 1940.

Perry, J. H. (ed.), *Chemical Engineers' Handbook*, 3rd ed., McGraw-Hill, N.Y., 1950.

Pharmacopeia of the United States of America, The (*The United States Pharmacopeia*), 15th revision (U.S.P. XV), United States Pharmacopœial Convention, Mack Pub. Co., Easton, Penna., 1955.

Radt, F. (ed.), *Elsevier's Encyclopædia of Organic Chemistry*, Elsevier, Houston, Texas, and Amsterdam, 20 Vols., 1946–.

Richter, V. von, *Chemistry of the Carbon Compounds*, 3rd ed. (trans. from 12th German ed.), Elsevier, Houston, Texas, and Amsterdam, Vols. I–IV, 1934–47.

Rodd, E. H. (ed.), *Chemistry of Carbon Compounds*, Elsevier, Houston, Texas, and Amsterdam, Vols. I–V, 1952–.

Rowe, F. M. (ed.), *Colour Index* (*C.I.*), 1st ed., Society of Dyers and Colourists, Bradford, Yorkshire, 1924; Supplement, 1928.

Schultz, G., and Lehmann, L., *Farbstofftabellen* (Sch.), 7th ed., Akadem. Verlag., Leipzig, 4 Vols., 1931–39. (Photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.)

Scott, W. W., *Standard Methods of Chemical Analysis*, Furman, N. H. (ed.), 5th ed., Van Nostrand, N.Y., Vols. I–II, 1939.

Seidell, A., *Solubilities*. Vol. I: *Solubilities of Inorganic and Metal Organic Compounds*; Vol. II: *Solubilities of Organic Compounds*; Vol. III: *Supplement to Volumes I and II*; 3rd ed., Van Nostrand, N.Y., 1940–52.

Sidgwick, N. V., *The Chemical Elements and Their Compounds*, Oxford Univ. Press, London, Vols. I–II, 1950.

Thorpe's Dictionary of Applied Chemistry, 4th ed., Longmans, Green, N.Y., 12 Vols., 1937–.

Ullmann, F., *Enzyklopädie der technischen Chemie*, 2nd ed., Urban & Schwarzenberg, Vienna, 11 Vols., 1928–32 (photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.); 3rd ed., 14 Vols., 1951–.

Walker, W. H., Lewis, W. K., McAdams, W. H., and Gilliland, E. R., *Principles of Chemical Engineering*, 3rd ed., McGraw-Hill, N.Y., 1937.

Weissberger, A. (ed.), *Technique of Organic Chemistry*, Interscience, N.Y.-London, 8+ Vols., 1948–.

Weissberger, A. (cons. ed.), *The Chemistry of Heterocyclic Compounds*, Interscience, N.Y.-London, 8+ Vols., 1950–.

PERIODICAL ABBREVIATIONS

The abbreviations used are, for the most part, those given in the "List of Periodicals Abstracted by Chemical Abstracts" (Vol. 45, No. 24, Pt. 2 (1951), also published separately). See also *Literature (survey)*, especially the sections on "Reviews, yearbooks, and monographs" and "Periodicals," Vol. 8, pp. 437–40.

Am. Soc. Testing Materials, Proc.	American Society for Testing Materials, Proceedings
Anal. Chem. (superseding *Ind. Eng. Chem., Anal. Ed.*)	Analytical Chemistry
Angew. Chem. (superseding *Die Chemie*; *Z. angew. Chem.*)	Angewandte Chemie
Ann. Chem., Justus Liebigs	Annalen der Chemie, Justus Liebigs
Arch. Biochem. and Biophys. (superseding *Arch. Biochem.*)	Archives of Biochemistry and Biophysics
Arch. Ind. Hyg. and Occupational Med. (superseding *J. Ind. Hyg. Toxicol.*)	Archives of Industrial Hygiene and Occupational Medicine
Biochem. J. (London)	Biochemical Journal, The
Biochem. Z.	Biochemische Zeitschrift
Biochim. et Biophys. Acta	Biochimica et Biophysica Acta
BIOS Repts.	British Intelligence Objectives Subcommittee Reports
Bull. Chem. Soc. Japan	Bulletin of the Chemical Society of Japan
Bull. soc. chim. or *Bull. soc. chim. France*	Bulletin de la société chimique de France
C.A.	Chemical Abstracts
Can. J. Research	Canadian Journal of Research
Chem. Ber. (superseding *Ber.*)	Chemische Berichte
Chem. Eng. (superseding *Chem. & Met. Eng.*)	Chemical Engineering with Chemical & Metallurgical Engineering
Chem. Eng. News (superseding *News Ed. (Am. Chem. Soc.); Ind. Eng. Chem., News Ed.*)	Chemical and Engineering News
Chem. Eng. Progress (superseding *Trans. Am. Inst. Chem. Engrs.*)	Chemical Engineering Progress with Transactions of American Institute of Chemical Engineers
Chem. Eng. Science	Chemical Engineering Science
Chemische Industrie	Chemische Industrie
Chemistry & Industry (formerly part of *J. Soc. Chem. Ind.*)	Chemistry & Industry
Chem. Revs.	Chemical Reviews
Chem. Tech. (Berlin) (superseding *Chem. Fabrik*)	Chemische Technik, Die (Berlin)
Chem. Week (superseding *Chem. Inds. Week*)	Chemical Week
Chem. Zentr.	Chemisches Zentralblatt
Chem.-Ztg.	Chemiker-Zeitung mit dem Sonderteil, Die Chemische Praxis und der Beilage, Chemisch-technische Übersicht
Chimica e industria (Italy) or *Chimica e industria (Milan)*	Chimica, La, e l'industria (Italy) or (Milan)
Chimie & industrie	Chimie & industrie
CIOS Repts.	Combined Intelligence Objectives Subcommittee Reports
Compt. rend.	Comptes rendus hebdomadaires des séances de l'académie des sciences
FIAT Repts.	Field Information Agency Technical Reports
Fortschr. chem. Forsch.	Fortschritte der chemischen Forschung
Gazz. chim. ital.	Gazzetta chimica italiana
Helv. Chim. Acta	Helvetica Chimica Acta
Ind. Chemist	Industrial Chemist and Chemical Manufacturer, The

Ind. Eng. Chem. (superseding *J. Ind. Eng. Chem.*)	Industrial and Engineering Chemistry
J. Agr. Food Chem.	Journal of Agricultural and Food Chemistry
J. Am. Chem. Soc.	Journal of the American Chemical Society, The
J. Am. Med. Assoc.	Journal of the American Medical Association, The
J. Am. Pharm. Assoc.	Journal of the American Pharmaceutical Association
J. Appl. Chem. (U.S.S.R.) (see also *Zhur. Priklad. Khim.*)	Journal of Applied Chemistry (U.S.S.R.)
J. Appl. Phys. (superseding *Physics*)	Journal of Applied Physics
J. Assoc. Offic. Agr. Chemists	Journal of the Association of Official Agricultural Chemists
J. Biol. Chem.	Journal of Biological Chemistry, The
J. Chem. Phys.	Journal of Chemical Physics, The
J. Chem. Soc.	Journal of the Chemical Society (London)
J. Colloid Sci.	Journal of Colloid Science
J. Electrochem. Soc. (superseding *Trans. Electrochem. Soc.*; *Trans. Am. Electrochem. Soc.*)	Journal of the Electrochemical Society
J. Gen. Chem. (U.S.S.R.) (see also *Zhur. Obshchet Khim.*)	Journal of General Chemistry (U.S.S.R.)
J. Indian Chem. Soc.	Journal of the Indian Chemical Society
J. Inst. Metals	Journal of the Institute of Metals and Metallurgical Abstracts
J. makromol. Chem. (superseding *J. prakt. Chem.*)	Journal für makromolekulare Chemie
J. Org. Chem.	Journal of Organic Chemistry, The
J. Phys. Chem. (superseding *J. Phys. & Colloid Chem.*)	Journal of Physical Chemistry, The
J. Polymer Sci. (superseding *J. Polymer Research*)	Journal of Polymer Science
J. Research Natl. Bur. Standards (superseding *Bur. Standards J. Research*)	Journal of Research of the National Bureau of Standards
J. Sci. Food Agr.	Journal of the Science of Food and Agriculture
J. Soc. Chem. Ind. or *J. Soc. Chem. Ind. (London)* (formerly containing *Chemistry & Industry*)	Journal of the Society of Chemical Industry (London)
J. Soc. Chem. Ind., Japan	Journal of the Society of Chemical Industry, Japan
Kolloid-Z.	Kolloid-Zeitschrift
Mfg. Chemist	Manufacturing Chemist and Pharmaceutical and Fine Chemical Trade Journal Incorporating Manufacturing Perfumer
Monatsh. Chem.	Monatshefte für Chemie und verwandte Teile anderer Wissenschaften
Nature	Nature
Nucleonics	Nucleonics
Office Tech. Services (OTS) Repts. (superseding *Office Publication Board Repts.*)	Office of Technical Services Reports
Oil, Paint Drug Reptr.	Oil, Paint and Drug Reporter
Phys. Rev.	Physical Review, The
Rec. trav. chim.	Recueil des travaux chimiques des Pays-Bas
Research (London)	Research, A Journal of Science and Its Applications
Revs. Mod. Phys.	Reviews of Modern Physics
Science	Science
Trans. Am. Inst. Mining Met. Engrs.	Transactions of the American Institute of Mining and Metallurgical Engineers
Trans. Am. Soc. Metals (superseding *Trans. Am. Soc. Steel Treating*)	Transactions of the American Society for Metals
Trans. Inst. Chem. Engrs. (London)	Transactions of the Institution of Chemical Engineers (London)
Z. anorg. u. allgem. Chem. (superseding *Z. anorg. Chem.*)	Zeitschrift für anorganische und allgemeine Chemie
Z. Elektrochem.	Zeitschrift für Elektrochemie und angewandte physikalische Chemie
Zhur. Obshchet Khim.	Zhurnal Obshchet Khimii (Journal of General Chemistry (U.S.S.R.))
Zhur. Priklad. Khim.	Zhurnal Prikladnoĭ Khimii (Journal of Applied Chemistry (U.S.S.R.)
Z. physik. Chem.	Zeitschrift für physikalische Chemie

T *continued*

THERMODYNAMICS

Thermodynamics deals with energy and its transformation, driving potential of a process, and equilibrium with reference to either physical change of state or chemical reaction. As the result of experience, three laws of thermodynamics have been developed as the backbone of thermodynamics. Based upon facts and basic principles of chemistry and physics, these laws have found wide applications to problems in various fields of engineering as well as in pure science.

In chemical technology, thermodynamics has been successfully applied in prediction of limiting conditions of unit operations or processes and the energy quantities involved. As a powerful and versatile tool in process research, development, design and operation, thermodynamics is indispensable in the solution of an ever-increasing number of process problems. During recent developments in petroleum refining, petroleum chemicals, synthetic rubber, plastics, synthetic fibers, and other synthetic organic chemicals, many new compounds and processes have been encountered. Only with the aid of thermodynamics has it been possible to get the most out of research and engineering effort. For instance, the process design can be performed by means of thermodynamic correlations of various thermochemical and phase equilibrium data without an excessive amount of pilot-plant work. The optimum operating temperature and pressure for a given chemical reaction can be predicted to save time-consuming effort in laboratories. This is especially important in making the cost estimate of a plant or preliminary proposal for an engineering service.

It must be emphasized that thermodynamics deals with equilibrium situations. It has nothing to say about the rate at which equilibrium is approached from any non-equilibrium situation. See *Equilibrium, chemical*; *Reaction kinetics.*

Basic Concepts and Definitions

System and Surroundings. The so-called system in thermodynamics designates a specific part of the material universe to be set apart for the purpose of study. It may consist of a single body, part of a body, or a number of bodies, large or small. The system can be either homogeneous or heterogeneous. The choice of a system, which depends largely upon the individual situation, may affect the analysis of a problem by thermodynamics. A wise choice of the system can provide a convenient route in

solving complex problems. With an improper selection of a system, some thermodynamic problems may even become unsolvable.

Once a system is specified, the rest of the universe becomes "surroundings." The term "surroundings" in thermodynamics refers more particularly to the surroundings immediately adjacent to the system. Between a system and its surroundings lies a boundary. In locating a boundary exactly between a system and its surroundings, the system can be unmistakably identified.

Several kinds of systems are frequently encountered. During the change of state, if there is no material flowing across the boundary between a system and its surroundings, the system is defined as a *closed system.* An *open system* is one involving the exchange of material across the boundary. In a multiphase system each separate phase is usually considered an open system wherein materials are flowing freely from one phase to the other, although the system as a whole may be a closed one.

A closed system may be free to absorb from or reject heat to the environment. It is also possible for a closed system to perform or to receive work. However, when the boundary between a system and its surroundings is made impervious to the heat flow, the closed system becomes *thermally isolated.* The closed system becomes *mechanically isolated* if a rigid boundary is present to prevent any volume change. When neither heat nor work is added or removed during a change of state, the closed system involved becomes a *completely isolated system.*

Two kinds of open systems are frequently encountered in industries, steady-state and unsteady-state. If the properties of any part of the system are constant regardless of the duration of an operation or a process, the so-called open system is a *steady-state flow system.* Most large-scale plants in industries which are operated continuously with a feed of constant composition at a carefully controlled operating condition belong to this class. On the other hand, if the properties of any part of a system undergo fluctuation and variation, the open system is an *unsteady-state flow system.* The compression of gases by a compressor into a storage tank is an example of this type of open system. The quantitative evaluation of a problem dealing with an unsteady-state flow system is more involved because the duration of the process becomes an additional variable.

State and State Function. To characterize any system it is necessary to find out the state in which the system exists. The term "state," in any thermodynamic discussion, is a kind of statistical average of the state assumed by all minute components of the system. This is a state in its gross sense, which is a macroscopic one. For instance, 10 cu. ft. of oxygen gas has its state completely defined if the temperature and pressure are given. The state of the oxygen so defined is a statistical average of the microscopic "states" of all individual oxygen molecules.

The variables which are used to characterize or to define completely the state of a system are called *state functions* or sometimes, simply, "properties." Once the state of a system is given, the "properties" or state functions are fixed irrespective of any changes undergone by the system. Although a system can have fixed values for different properties at a given state, the minimum number of properties required to define the state of a system at equilibrium is determined by the number of components and phases present in the system. This minimum number of properties is identified as the degrees of freedom. The quantitative relation known as the phase rule is:

$$F = C - P + 2 \tag{1}$$

See *Phase rule.*

Process. Any change of state taking place in a system is called a *process.* The process can be either a physical change of state or a chemical reaction. In other words, "process" as used in thermodynamics refers to unit operations as well as to unit processes.

Depending upon the limitation imposed upon a system during a process, special kinds of processes can be distinguished. An *adiabatic process* is one in which no heat flows across the boundary between the system and its surroundings; an *isobaric process* takes place at constant pressure. In general, it is desirable to have a chemical reaction carried out as an *isothermal process*, for this leads to a higher equilibrium conversion in either an endothermic or an exothermic reaction. In most organic reactions a large number of undesirable side reactions accompany a main reaction. The control of reaction at one uniform temperature throughout the reactor can either eliminate or reduce the extent of the side reactions.

On the other hand, it is always more economical to carry out some unit operations, such as fractional distillation, evaporation, other heat exchanges, and drying adiabatically. In gas absorption, where a large amount of heat is evolved, isothermal operation is desirable to obtain the maximum recovery.

Heat Reservoir. This is an ideal piece of equipment conceived for the convenience of theoretical thermodynamic treatment. A heat reservoir, as normally referred to in thermodynamic consideration, is one of infinite capacity. Any transfer of a finite quantity of heat in or out of the heat reservoir has a negligible effect on its temperature. The ocean and the atmosphere are practical examples that approach this type of heat reservoir.

Reversible and Irreversible Processes. The rate of a process can always be expressed as follows:

$$\text{Rate} = \frac{\text{driving force}}{\text{resistance}}$$

When all the forces acting upon a system are balanced, the driving force for a change of state is equal to zero, and the rate of a process becomes zero. Under this condition a system is said to be at equilibrium, and its state remains the same.

For a *reversible process* the driving force is made infinitesimally small. This makes the rate of a process negligibly small, so that a truly reversible process would require an infinite number of years before reaching its final state. Since the driving force in one direction is almost equal to zero, its direction can easily be reversed by an extremely small external force. On the other hand, an *irreversible process* is one proceeding under a driving force of finite order of magnitude. All actual processes are spontaneous, proceeding at a finite rate, and are therefore irreversible. However, an irreversible process can be made to approach a reversible one by some device with a suitable choice of conditions.

Consider a process involving the expansion of a gas against a piston in a vertical cylinder. To simplify the explanation, it is assumed that the piston and piston rod have no weight of their own. The gas inside the cylinder has an initial pressure of 10 atm. and is allowed to expand to 1 atmosphere pressure. If the pressure acting on the outside of the piston is 1 atm., the piston will continue to move upward, with a variable speed of finite order of magnitude, until the pressure of the gas inside the cylinder becomes identical with the outside pressure, that is, 1 atm. This actual process of expansion is irreversible because it proceeds under a driving force greater than an

infinitesimal amount. It starts with a driving force equal to 9 atm. As the expansion proceeds, the pressure inside the cylinder decreases until finally it is 1 atm., which is identical with the outside pressure. At this point the driving force is equal to zero and the expansion ends.

The same process can be made reversible from the initial to the final state. At the start of expansion, an infinite number of weights, each of which has an infinitesimally small mass, are placed upon the piston. The total weight of these weights is equivalent to a pressure identical with that of the gas inside the cylinder. By removing the weights one by one, the expansion of the gas inside the cylinder can be made to take place under an infinitesimal driving force from the beginning to the end. Although it requires an infinite time for its completion, the expansion of the gas inside the cylinder becomes a reversible process.

Chemical reactions, as well as physical changes of state, can be carried out in a reversible way, even though the actual chemical reactions take place spontaneously and are irreversible. Ionic reactions can be carried out in a galvanic cell to produce e.m.f. between two electrodes. If an external source of e.m.f. of opposite direction is applied to such a cell, the chemical reaction can proceed reversibly if the counter e.m.f. is infinitesimally smaller than the e.m.f. of the cell, and the chemical reaction can easily be reversed by increasing the counter e.m.f. an infinitesimal amount. An infinite time is required to conclude the chemical reaction reversibly.

All actual processes are irreversible. The reversible process, which brings no frictional loss, is an idealized process never in existence. The purpose of the concept of the reversible process is to establish a standard for the study of performance of actual processes which are irreversible. A reversible execution of a process involves no frictional loss and represents the maximum accomplishment or maximum efficiency theoretically possible. With the reversible process as a yardstick, a chemical engineer or technologist can determine whether an actual process is efficient or needs further improvement.

Work. Work is the result of action by a system against an external force. It can be expressed as the product of an intensity factor and a capacity factor. In mechanical work the intensity factor is the force and the capacity factor is the distance, measured along the direction of the force, through which the load is moved.

$$W = \int_{L_1}^{L_2} F \, dL \tag{2}$$

If the mechanical work is done by or against a fluid pressure, the force F is equal to the product of external pressure P_e and area of cross section A normal to the acting pressure. Equation (2) can be transformed into:

$$W = \int_{V_1}^{V_2} P_e \, dV \tag{3}$$

where V_1 and V_2 are the initial and final volumes of the fluid.

If the process is reversible, the external pressure P_e is equal to $P \pm dP$, where P is the pressure of the fluid. In substituting this into equation (3), the work in a reversible process becomes:

$$W = \int_{V_1}^{V_2} (P \, dV \pm dP \, dV) \tag{4}$$

Since the second term is negligible compared to the first, equation (4) takes the form:

$$W = \int_{V_1}^{V_2} P \, dV \tag{5}$$

To evaluate the integral, a relation between the pressure and volume of the fluid must be known.

If a process is conducted under constant pressure, the pressure term can be taken out of the integral and the work becomes the product of pressure and volume change.

The Three Laws of Thermodynamics

Three laws of thermodynamics are merely statements of human experience based upon a broad foundation of facts and sound reasoning. The first two laws were developed in the latter half of the last century. Since their development, the first and second laws of thermodynamics have found an amazingly wide application to numerous problems in engineering and pure science. The third law was developed in the present century. It limits the value of entropy defined by the second law and therefore finds its application in the treatment of chemical equilibrium.

THE FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is the law of conservation of energy. Energy cannot be either created or destroyed. If an amount of energy disappears at one place, an equivalent amount of energy must appear at another place. If an amount of energy disappears in one form, an equivalent amount of energy will appear in another form. Heat and work are some forms of energy which are measurable outside of a system. On the other hand, energy can also be stored in a system instead of passing freely, in the form of heat or work, from one system to another. This stored energy, which is defined as internal energy or energy content, is a definite property, or state function, of a system. This means that the change in internal energy of a system depends upon the initial and final states and is independent of the path of the process. In a cyclic process, where a system comes back to the original state after a series of processes, the internal energy of the system at the final state is identical with that at the start.

Closed System or Nonflow System. For any process the increase in internal energy of a closed system is always equal to the amount of heat absorbed minus the work done by the system. Mathematically, it can be represented by:

$$\Delta U = Q - W \tag{6}$$

For a cyclic process there is no net change of internal energy. The amount of work performed by a system is just equivalent to the amount of heat absorbed by the system.

In making numerical substitution into equation (6), Q has a *positive* sign if it is the *heat absorbed by* the system, but it is otherwise with W, which has a *positive* value if it is *work done by* the system.

In addition to the convention about the sign for the work and heat terms, the units of each term in equation (6) should be consistent throughout. If Q is expressed in B.t.u. per pound of a system, the other terms, ΔU and W, should be in the same units. If foot-pounds are preferred as the units, ΔU and Q as well as W should be expressed in foot-pounds.

Equation (6) applies strictly only to a closed or nonflow system. For an infinitesimal process, it takes the following form:

$$dU = \delta Q - \delta W \tag{7}$$

The differential sign d is used only for the internal energy, not for the heat and work. Since internal energy is a state function, the differential dU is sometimes referred to as an exact differential. On the other hand, the heat and work effect in a process depends upon the path of the process as well as the initial and final states of a system, and for these the differential sign δ is used. In integrating dU, the result is $U_2 - U_1$, which represents an increase in internal energy, but the integrals of δQ and δW cannot be written as $Q_2 - Q_1$ or $W_1 - W_2$, because this would be true only if the path of a process had no effect upon the result. The integrated expressions of δQ and δW are Q and W as previously defined.

Unsteady-Flow System (25). With reference to Figure 1, consider a large body and a small mass dm. The internal energy of the big body is represented by U_1 at the initial state and by U_2 at the final state. At the initial state the small mass is at a position X feet higher than its final state, at which the small mass comes to rest within the boundary of the big body. One possible example of such an unsteady-state flow

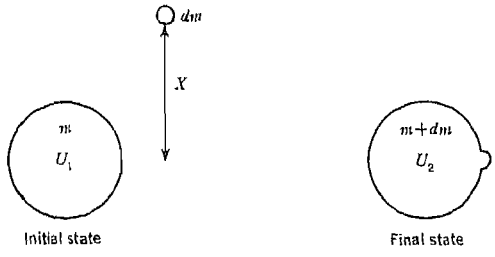


Fig. 1. Unsteady-state flow system.

system would be the compression of a gas into a well-insulated tank by a compressor. At every differential compression stroke a small amount of mass dm is added to the larger mass in the tank.

The small mass dm has a specific volume V (cubic feet per pound), linear velocity, u (feet per second), pressure P' (pounds per square foot), and internal energy U' (foot-pounds per pound). During the change of state the big body absorbs an amount of heat Q and performs an amount of work W upon the surroundings. Consider the big body and small mass as a compound system; its total amount of energy at the initial state must be equal to the summation of internal energy of both big body and small mass, potential and kinetic energy of the small mass. The total energy of the system at the final state is equal to the internal energy of the big body including the absorbed small mass. The increase of energy of the system from the initial to the final state must be equal to the difference between heat and work effect during the process as given by:

$$Q - (W - W') = U_2 - \left\{U_1 + dm\left(U' + \frac{u^2}{2g_c} + X\right)\right\} \tag{8}$$

The second work term W' in equation (8) is due to that done, as the result of volume change, by the surroundings upon the compound system. The small mass dm is completely brought into the boundary of the big body of the final state under its own constant pressure P. The work term W' is therefore equal to the product of pressure P and the volume change of the compound system due to the absorption of

the small mass. This volume change is equal to the volume of the small mass. Equation (9) gives such a mathematical expression for W':

$$W' = (P)(V\,dm) \tag{9}$$

Substituting equation (9) into (8):

$$Q - W = U_2 - U_1 - \left(U' + PV + \frac{u^2}{2g_c} + X\right) dm \tag{10}$$

The frequent occurrence of the $U + PV$ term in thermodynamic calculations prompted the definition of a new term, *enthalpy*. Enthalpy, H, is therefore mathematically given by:

$$H = U' + PV \tag{11}$$

In introducing the definition of enthalpy, equation (10) takes the following form:

$$Q - W = U_2 - U_1 - \left(H + \frac{u^2}{2g_c} + X\right) dm \tag{12}$$

Considering a number of small masses at different conditions flying in and out during the process, equation (12) can be generalized by taking the summation of the terms containing small masses. A general expression of the first law applicable to any open system then takes the form:

$$Q - W = U_2 - U_1 \pm \sum_{m_i}^{m_i} \left(H + \frac{u^2}{2g_c} + X\right) dm \tag{13}$$

The sign before the summation term becomes positive if the process involves a transfer of a small mass out of a large body.

Equation (13) is especially valuable for unsteady-state flow systems. In the example mentioned above, the compression of a gas into a well-insulated tank by a compressor, the pressure of the gas inside the tank is continuously built up and the condition of the gas at the exit of the compressor is continuously changed. If the gas in the tank is considered as a large body, equation (13) is applicable to such a process in which a certain amount of gas is brought into the tank. The temperature and amount of gas present at the end of expansion can thus be calculated.

Steady-State Flow System. During steady-state flow operation a fluid is uniform and constant in composition, state, and velocity at the entrance and at the exit. With the mass rates of flow into and out of the open system constant and equal, the state of the fluid in any part within the system is identical at all times. This means that the internal energy of the open system is the same irrespective of duration of the process; that is, $U_2 = U_1$.

Equation (13) can now be reduced to:

$$Q - W = \pm \sum_{m_i}^{m_i} \left(H + \frac{u^2}{2g_c} + X\right) dm \tag{14}$$

Consider as a basis a unit mass of fluid flowing through the open system. Equation (14) will be transformed into the following expression by placing a positive sign before the terms for one pound of fluid at the exit (subscript 2), and a negative sign before the terms for the fluid at the inlet (subscript 1):

$$Q - W = \left(H_2 + \frac{u_2^2}{2g_c} + X_2\right) - \left(H_1 + \frac{u_1^2}{2g_c} + X_1\right) \tag{15}$$

Equation (15) is the first-law expression for a steady-state flow system (in the absence of magnetic or surface tension effect, etc.). Its differential form is:

$$\delta Q - \delta W = dH + \frac{u\,du}{g_c} + dX \tag{16}$$

The energy balance of a steady-flow system can also be made with reference to a specific kind of energy, such as mechanical energy. This mechanical-energy balance is the basis of Bernoulli's theorem, which has been extensively used in fluid dynamics. See *Fluid mechanics.*

In deriving the equation of mechanical-energy balance from equation (15), those terms which are not mechanical energy can be dropped. These nonmechanical energy terms are heat absorption Q and internal energies at the inlet and exit, U_1 and U_2. The frictional loss F' is part of the mechanical-energy output. In the case of a compressible fluid the self-expansion of the fluid brings into the system an additional input in mechanical energy. The resulting equation of a complete mechanical-energy balance for a steady-state flow system thus takes the form:

$$-F' - W = \left(P_2V_2 + \frac{u_2^2}{2g_c} + X_2\right) - \left(P_1V_1 + \frac{u_1^2}{2g_c} + X_1\right) - \int_{V_1}^{V_2} P\,dV \tag{17}$$

Since

$$P_2V_2 - P_1V_1 = \int_{V_1}^{V_2} d(PV) = \int_{V_1}^{V_2} P\,dV + \int_{P_1}^{P_2} V\,dP \tag{18}$$

equation (17) becomes:

$$-F' - W = \frac{u_2^2 - u_1^2}{2g_c} + (X_2 - X_1) + \int_{P_1}^{P_2} V\,dP \tag{19}$$

The equation of mechanical-energy balance takes the following form for a differential process:

$$-\delta F' - \delta W = \frac{u\,du}{g_c} + dX + V\,dP \tag{20}$$

For the purpose of calculation, all terms in equations (8) to (20) must be expressed in the same units.

Important Cases of Flow Equation (70). The first-law expression for a steady-state flow system is widely used in solving various problems in the design and operation of such equipment as fractionating towers, evaporators, condensers, crystallizers, heat exchangers, and dryers. It has also been used as a major tool in analyzing various power-plant cycles. In predicting the performance of an expansion or compression, the first law is the basis of the modern refrigeration cycle (see *Refrigeration*).

In the general case of fluid flow through a process plant the amount of heat absorption by the system is negligible if the piping and equipment are well insulated so that q may be considered equal to zero. The flow equation then is reduced to the following special form:

$$-W = (H_2 - H_1) + (X_2 - X_1) + \frac{u_2^2 - u_1^2}{2g_c} \tag{21}$$

In the case of an adiabatic steam engine or turbine, the heat term drops out. The differences in potential and kinetic head are both negligible. The flow equation is simplified to:

$$-W = H_2 - H_1 \tag{22}$$

According to equation (22), the work delivered is equal to the decrease in enthalpy of the steam flowing through a steam turbine or engine.

For fluid flow through a nozzle, as in a spray dryer, for example, there is no work effect. The heat term and difference in potential head are negligible, and the resulting flow equation becomes:

$$\frac{u_2^2 - u_1^2}{2g_c} = H_1 - H_2 \tag{23}$$

In this case the high velocity at the tip of nozzle can be calculated by the enthalpy change of steam across the nozzle. For a fluid flowing through an insulated valve, regulator, or any instrument involving a significant pressure drop, all terms in the flow equation except enthalpy become negligible. This kind of expansion is known as Joule-Thomson expansion, the characteristic of which is given by the simplified flow equation, $H_2 - H_1 = 0$, or:

$$H_2 = H_1 \tag{24}$$

The enthalpy per pound of fluid before and that after the expansion are identical. This relation of constant enthalpy holds when the velocity of flow is not exceedingly high, an assumption which is justified in most flow problems in process industries.

When the flow equation is applied to a fractionating tower, evaporator, condenser, or other heat exchanger, the same simplified equation always results. There is no external work effect, potential and kinetic energy effects are negligible, and the flow equation becomes:

$$Q = H_2 - H_1 \tag{25}$$

The Q term in equation (25) is heat gained by the system; thus it is equal to heat *loss* of the equipment *to* the surroundings, with a *minus* sign. In low-temperature distillation the Q term in equation (25) is the heat leakage into the fractionating column. If the equipment is well insulated, the heat loss, $-Q$, is negligible. In this case the enthalpy of input streams is equal to that of exit streams. This is known as enthalpy balance and is widely used in design calculations.

Enthalpy, like internal energy, is an extensive property, and it must be expressed per pound (or per other weight unit). Again like internal energy, it has no absolute value and enters into all problems only as a difference. It is convenient to choose a reference state at which the enthalpy is assigned zero value. The enthalpy value at any other temperature and pressure is then calculated with the heat capacity and P-V-T data.

The choice of standard state is entirely arbitrary, depending upon the nature of the problem. Normally, the pure compound in the saturated liquid phase at its freezing point is selected as reference state and assigned the zero value for its enthalpy (see also *Thermochemistry*). With the data on specific heats of pure compounds and their heats of mixing available, the enthalpy values of mixtures as well as of pure compounds can be calculated if the pressure is not too high.

The most logical standard state is the element at 0°K. This selection of standard states puts the enthalpy values of elements, and of compounds, which are formed of elements, on the same basis. The enthalpy values thus derived can be directly used in the algebraic manipulation to calculate the heat of reactions as well as the enthalpy

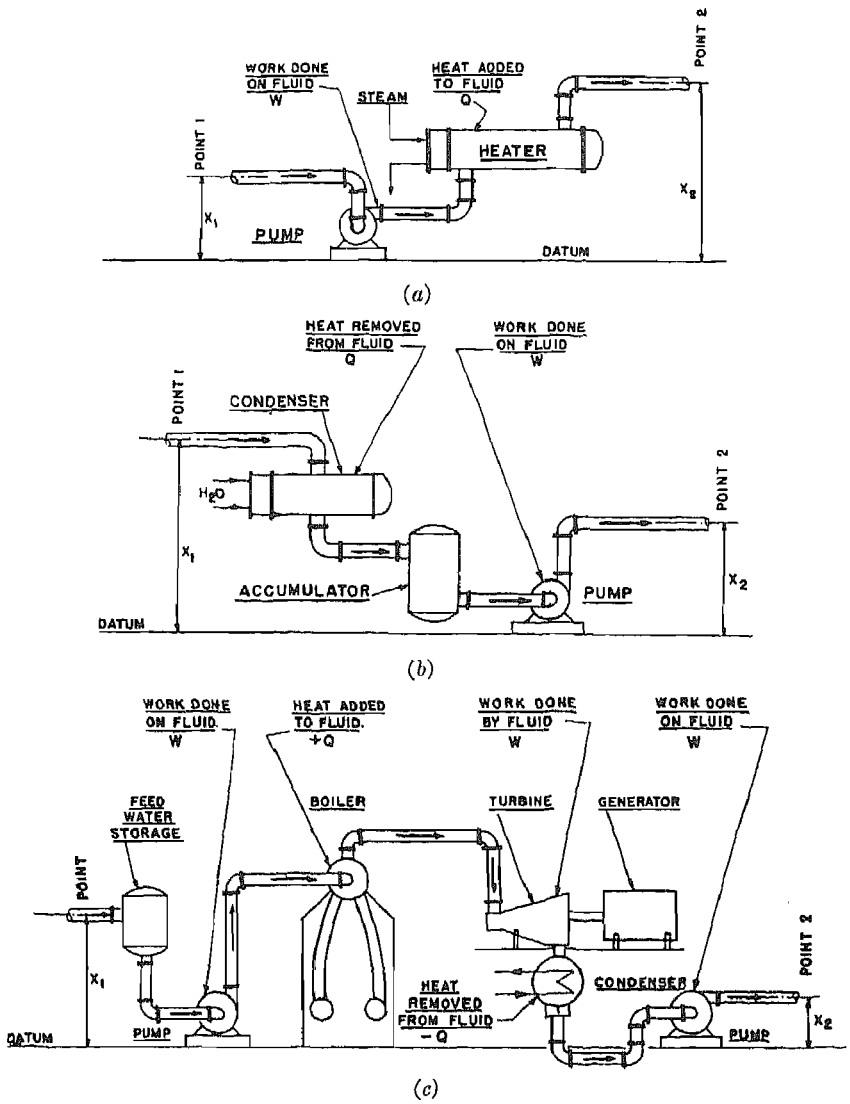


Fig. 2. Example of steady-state flow processes (ref. 16, **26**, No. 8, 87 (1947)). (*a*) Work done on fluid and heat added to fluid. (*b*) Heat removed from fluid and work done on fluid. (*c*) Work and heat added to fluid, work done by fluid, heat removed from fluid, and work done on fluid.

of the mixture resulting from physical mixing of compounds. On the selection of reference state see also *Thermochemistry*.

Figure 2 shows examples of steady-state flow processes, illustrating the first law of thermodynamics.

A careful analysis by the steady-state flow equation frequently leads to a process improvement. For example, a vapor re-use process was developed by Othmer (14,36), after such analysis, to overcome the practical difficulties of a multiple-effect fractionation as well as to reduce heat requirement. This is illustrated in Figure 3. The first column (numbered 3) operates at an elevated pressure with live steam. The vapor from this column is used as a heating medium and condensed in the reboiler of the second column, which operates at atmospheric pressure. The condensate from the reboiler of the second column is introduced as the feed to this column, which separates the mixture into two substantially pure components without any additional requirement of steam.

Nonisothermal Flow of Compressible Fluids. The flow of a compressible fluid at velocity u through heated pipe or tubing is accompanied by changes in both temperature and density. Starting with the equation of mechanical-energy balance, equation (20), the elimination of work and potential-energy effect in this case yields:

$$-V\,dP = \frac{u\,du}{g_c} + dF' \tag{26}$$

The frictional loss dF' through a pipe of length dL and inside diameter D_i is given by Fanning's equation:

$$dF' = \frac{u^2}{g_c}\frac{2f}{D_i}dL \tag{27}$$

where f is the Fanning friction factor. The linear velocity u is related to the mass rate w, specific volume V, and cross-sectional area normal to the flow, A, by the following equation:

$$u = wV/A \tag{28}$$

For a steady-state flow in a pipe of uniform cross section, w/A is a constant. Differentiating equation (28):

$$du = w\,dV/A \tag{29}$$

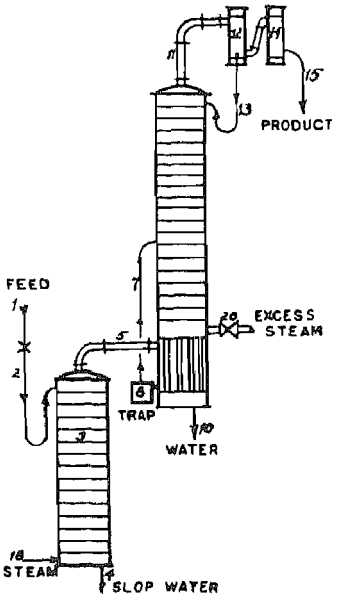


Fig. 3. Othmer's vapor re-use process (37).

Substituting equations (27), (28), and (29) into (26) and dividing each term of the resulting equation by Vw^2/gA^2, one obtains:

$$\frac{-g_cA^2}{w^2}dP = dV + \frac{V.2f\,dL}{D_i} \tag{30}$$

Consider one mole of the gas as a basis. The relation between pressure, temperature, and volume of the real gas is represented by the following equation of state:

$$PV = ZRT \tag{31}$$

where Z is the compressibility factor. Differentiating equation (31):

$$dV = \frac{R}{P}(Z\,dT + T\,dZ) - \frac{V\,dP}{P} \tag{32}$$

Substituting equation (32) into (30) and dividing each term by ZR/P:

$$\frac{-g_c A^2 P\, dP}{ZRw^2} = dT - \frac{T\, dZ}{Z} - \frac{T\, dP}{P} + \frac{2f\, T\, dL}{D_i} \tag{33}$$

Another relationship in formulating the nonisothermal flow of a compressible fluid is given by the heat balance across the differential length of the pipe:

$$wC_p\, dT = q\pi D_i\, dL \tag{34}$$

where q is the heat flux; the rate of heat transfer per unit area of heat transfer surface (which is the pipe wall in the present case). Upon integrating equation (34) from the entrance end of the pipe to any point in the pipe, one obtains the expression for the temperature T at that point in the pipe:

$$T = T_1 + \frac{q\pi D_i L}{w(C_p)_m} \tag{35}$$

where T_1 is the temperature of the fluid at the entrance end of the pipe, $(C_p)_m$ is the mean heat capacity of the fluid between temperatures T_1 and T. In substituting equations (34) and (35) into (33), the final working equation for the nonisothermal flow of a compressible fluid is obtained:

$$\left[\frac{-g_c A^2 P}{ZRw^2} + \frac{T_1}{P} + \frac{q\pi D_i L}{Pw(C_p)_m}\right] dP = \left[\frac{q\pi D_i}{wC_p} + \frac{2fT_1}{D_i} + \frac{2\pi fqL}{w(C_p)_m}\right] dL - \left[T_1 + \frac{q\pi D_i L}{w(C_p)_m}\right] d\ln Z \tag{36}$$

If the compressibility changes little throughout the pipe, the second term on the right side of equation (36) can be dropped out. In solving this equation the data for the compressibility factor, as well as the friction factor chart, must be available. However, equation (36) is too complex to yield an integrated expression by a straightforward solution. It must be solved stepwise, by trial-and-error procedure, calculating the pressure drops for each short and successive length from the entrance to the end of the pipe. For each successive length (positive or negative) of the pipe, assume a pressure drop and evaluate both sides of equation (36). If the assumed pressure drop for that length of the pipe is right, the term on the right side of the equation is equal to that on the left. Otherwise try another value for pressure drop until equation (36) is satisfied.

Heats of Reaction. It often happens that data on the heat of a reaction are not available for the temperature at which the reaction is actually carried out in the plant. For example, in the older literature heats of reaction were usually given at 18°C. For the calculation of the heat of reaction at one temperature from the data for another temperature, see *Thermochemistry*.

Heat Effect in a Batchwise Process. Batch practice is not uncommon in process industries, especially when a large number of products are produced, each in relatively small quantity. Such is often the case in the manufacture of dyes, dye intermediates, and fine chemicals.

The heat effect in a batchwise chemical process can be evaluated by the application of the first law to the reacting system inside a converter. Thus the heat effect is:

$$Q = \Delta U + W \tag{6}$$

if the only work involved is mechanical work, $W = \int_1^2 P\,dV$. In substituting the enthalpy term into equation (6):

$$Q = \Delta H - (P_2 - P_1)V \tag{37}$$

In this equation ΔH is the enthalpy change due to the chemical reaction and can be evaluated by the method discussed previously. V, the volume occupied by the reaction system, is maintained constant during the process.

If the reaction is a homogeneous one in a gas phase only, the equation of state involving compressibility factor can be used. Equation (37) can be further transformed (at constant T) into:

$$Q = \Delta H - RT(N_P Z_P - N_R Z_R) \tag{38}$$

where N_R and N_P are the total number of moles of reactants and products. N_P also includes the excess reactants, and N_R and N_P include inert components. Z_P and Z_R are the compressibility factors for products and reactants.

THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics has been variously expressed (14,19,23). In 1851 Clausius stated the second law this way: "It is impossible for a self-acting machine, unaided by any external agency, to convey heat from one body to another at a higher temperature." Kelvin gave the second law thus: "It is impossible by means of an inanimate material agency to derive mechanical effect from any portion of matter by cooling it below the temperature of surrounding objects." As an improvement over Kelvin's statement, Planck said: "It is impossible to construct a machine which will operate in a cycle and produce no effects but the raising of a weight and the cooling of a heat reservoir." Such a possibility is sometimes referred to as perpetual motion of the second kind as contrasted with the possibility of violating the first law of thermodynamics.

With reference to any particular system in any process, the second law can be expressed in terms of many special statements. For example, with reference to a mixture of two gases, it would be contrary to the second law if a gaseous mixture were to separate into the pure compounds by itself without any external effort. In other words, it is a spontaneous process when two gases are brought together to form a mixture, but the separation or unmixing of a mixture is not a spontaneous process taking place all by itself.

Consider a chemical reaction taking place at a given temperature. The reactants at a certain state are transformed into products at a certain state. By the first law the amount of heat effect accompanying the reaction can be calculated. However, there are a large number of questions which can never be answered by the first law. Can the reaction actually proceed from the reactants to products at a given condition? Where is the point of equilibrium at which the composition of the reacting system will remain the same? There are a large number of variables affecting the equilibrium point. How do these factors, such as temperature, pressure, and feed composition, affect the equilibrium in a quantitative way? In an endothermic reaction, how can the reaction proceed spontaneously? These are questions of prime importance which can be answered only by the application of the second law.

In the transfer of heat the difference in temperature is the driving force which permits the heat to flow only from a high to a low temperature level. The transfer of

heat from a low temperature to a high temperature level cannot take place by itself because it is against the direction of the driving potential. However, with external work available outside the system, it is possible to reverse the direction of heat transfer. A practical illustration of this is refrigeration. The work delivered by a compressor enables a refrigerating fluid to absorb heat continuously from a relatively cooler spot and to reject heat to a higher temperature level.

When oxygen and nitrogen are brought together, the mixing of two gases proceeds spontaneously under a driving potential which is the difference in the partial pressures of oxygen and nitrogen. Although the automatic separation of a gaseous mixture is against the direction of the driving force, the production of oxygen from air is achieved on a large scale by low-temperature fractionation. This reversal of a mixing is made possible only by supplying energy and work from an external source during fractional distillation.

As a more general statement, the second law can probably be expressed in the following words: A process that actually takes place must proceed spontaneously in the direction of its driving potential, and it cannot be reversed without the aid of an external agency.

Mathematical Definition of Entropy. Entropy is a term defined mathematically for the purpose of quantitative treatment of the second law of thermodynamics. For an infinitesimal change of state, if an amount of heat δQ is absorbed by a system reversibly, the change of entropy of the system is given by:

$$dS = \delta Q/T \tag{39}$$

where S designates the entropy of the system, and T is the temperature of the system on an absolute scale. From the definition, the amount of heat absorbed by a system is a partial measure of the magnitude of its entropy increase. However, the same quantity of heat absorbed may not represent the same increase in entropy. Entropy increase at high temperature level is smaller than that at lower temperature with the same amount of heat absorption. In evaluating the amount of heat absorbed for the calculation of entropy increase, the process involved has to be reversible. In an irreversible process the entropy increase of a system is always greater than that corresponding to its heat absorption.

Carnot Cycle and Its Generalization. As a standard in evaluating the efficiency or performance of actual power cycles, the Carnot cycle is a hypothetical cyclic process producing maximum conversion of heat into work. It consists of an engine or work-doing mechanism operating between two heat reservoirs at two temperature levels. The working fluid in the engine is a "perfect" gas. Each cycle consists of four steps and each step is a reversible process. The first step is a reversible isothermal expansion of the gas inside the cylinder of the engine. During this process, an amount of heat Q_1 is transferred from the heat reservoir to the gas, which is kept at constant temperature T_1 during the expansion. The second step involves an adiabatic and reversible expansion which brings the temperature of the gas to T_2, the lower temperature level. The third step is a reversible and isothermal compression during which an amount of heat $-Q_2$ is rejected from the gas into a second heat reservoir at a temperature T_2. During this isothermal compression the gas in the cylinder is brought to such a pressure that after the last step of adiabatic compression the gas will be back at its original condition of temperature and pressure.

In the Carnot cycle, whenever the heat is transferred, it is transferred under an

infinitesimal difference of temperature. The expansion or compression is also conducted reversibly, with an infinitesimal difference of pressure as a driving force. By the first law, the net work produced during each cycle is:

$$W_{net} = Q_1 + Q_2 \tag{40}$$

The efficiency of the cycle is defined as the ratio of the net work to the heat absorbed by the gas at T_1. The efficiency of the Carnot cycle is therefore:

$$\text{Eff.} = \frac{W}{Q_1} = \frac{Q_1 + Q_2}{Q_1} \tag{41}$$

During the isothermal expansion or compression, heat absorbed by the perfect gas is exactly equal to the work produced. Therefore:

$$Q_1 = \int_{V_1}^{V_2} P\,dV = RT_1 \ln \frac{V_2}{V_1} \tag{42}$$

and

$$Q_2 = \int_{V_3}^{V_4} P\,dV = RT_2 \ln \frac{V_4}{V_3} \tag{43}$$

where V_1, V_2, V_3, V_4 refer to the molal volume of the perfect gas at the beginning of steps 1, 2, 3, and 4 respectively. As steps 2 and 4 are adiabatic and reversible, the perfect gas law leads to the expression:

$$\frac{V_2}{V_1} = \frac{V_3}{V_4} \tag{44}$$

Substituting equation (44) into (42):

$$Q_2 = -RT_2 \ln \frac{V_2}{V_1} \tag{45}$$

On substituting equations (42) and (45) into (41) the expression for the efficiency of a Carnot cycle becomes:

$$\text{Eff.} = \frac{Q_1 + Q_2}{Q_1} = \frac{T_1 - T_2}{T_1}$$

or

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} = 0 \tag{46}$$

It may be noted that the two terms in equation (46) are equivalent to the entropy change of steps 1 and 3 in the Carnot cycle. The entropy of the system in the second and fourth steps, which are adiabatic and reversible operations, undergoes no change. The net entropy change for the system operating in a Carnot cycle is equal to zero.

The conclusion regarding the entropy change in a Carnot cycle can be extended to any reversible cycle of changes for any working substance (14). Such a cycle can be represented on a pressure-volume diagram as in Figure 4. Consider the cycle to be broken into four Carnot cycles represented by the areas I, II, III, and IV. The summation of these four Carnot cycles is not exactly equal to the reversible cycle. The

difference is represented by the crosshatched areas. For each of the Carnot cycles the following equations, similar to equation (46), hold:

$$\left[\frac{Q_1}{T_1} + \frac{Q_2}{T_2}\right]_{\text{I}} = 0 \qquad \left[\frac{Q_1}{T_1} + \frac{Q_2}{T_2}\right]_{\text{II}} = 0 \tag{47}$$

Adding these equations:

$$\sum \frac{Q}{T} = 0 \tag{48}$$

The reversible cycles can be broken into a larger number of Carnot cycles by taking the adiabatic curves of each Carnot cycle closer together. In this way the summation of the Carnot cycles will be more closely equal to the original reversible cycle. By making each isothermal step a differential one, the adiabatic steps can be so close to each other that an infinite number of Carnot cycles will result. In this limiting case the difference between the original reversible cycle and the Carnot cycles, as represented by the crosshatched areas in Figure 4, becomes negligible. The summation of terms in equation (48) at this limit is represented by an integral:

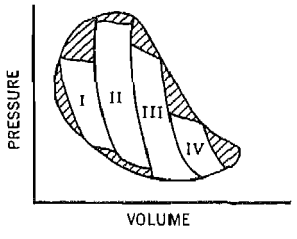


Fig. 4. Entropy change of a reversible cycle.

$$\text{Limit} \sum \frac{Q}{T} = \oint \frac{\delta Q_{\text{rev.}}}{T} = \oint dS \tag{49}$$

This equation defines a very important aspect of entropy. For any reversible cyclic process the entropy change of a given system is equal to zero. This means that dS is an exact differential. Entropy S, which has a definite value characteristic of a given state, is therefore a state function. Like enthalpy and internal energy, entropy is also an extensive property which is directly proportional to the mass of a system.

Entropy Change in Irreversible Processes. The change in the entropy of a system depends upon its initial and final states, irrespective of the path of the process. Between a given initial state and final state, the entropy change along an irreversible process is identical with that in a reversible process.

All actual processes are irreversible. To find the entropy change in an irreversible process, the steps involved are:

First identify the initial and final states of the irreversible process. Devise a reversible path between the initial state and the final state of the irreversible process. Along the devised reversible path, evaluate the entropy change by the equation which defines the entropy:

$$\Delta S = \int_1^2 dS = \int_1^2 \frac{\delta Q}{T} \tag{50}$$

The value of entropy change thus obtained is equal to that for the irreversible process.

For a reversible process the entropy change of a system is always exactly equal to that of the surroundings with opposite sign. Taking the system and its surroundings as a whole, there is no heat and work effect across the boundary of this compound system. This compound system is called an isolated system. For any isolated system the entropy undergoes no change if a reversible process is involved. Take the Carnot cycle as an illustration. In the first step, which is an isothermal and reversible

expansion, an amount of heat Q_1 is transferred reversibly from the heat reservoir at a temperature differentially higher than T_1, that is, $T_1 + dT$, to the gas at T_1 inside the cylinder. The heat capacity of the cylinder is assumed to be negligible. The entropy change of the perfect gas inside the cylinder is equal to Q_1/T_1. The entropy change in the surroundings, which is the heat reservoir, is equal to $-Q_1/(T_1 + dT)$. Since dT is a quantity infinitesimally small, the entropy changes in the system and its surroundings are equal in magnitude but different in sign. The gas and the heat reservoir constitute an isolated system in which the total change of entropy for a reversible process is equal to zero. While no entropy change is involved in the system during the second and fourth steps, the total entropy change in the third step, an isothermal and reversible compression, is again equal to zero when the gas and heat reservoir is taken into consideration.

Physical Significance of Entropy (14,23). Entropy is an extensive property of a system. An increase in entropy signifies a decrease in the availability or capacity of a system for producing work. Like other state functions, entropy has its magnitude completely determined by the state of the system, regardless of its external position or motion relative to the surroundings. Thus the entropy of a flywheel in rotation is not different from that of the same flywheel at rest, as long as the temperature and pressure are identical in both cases.

Entropy change in a process measures the amount of energy which has become unavailable for producing work. By solving equations (41) and (46), the work obtained in a Carnot cycle is given by:

$$W = Q_1 \frac{(T_1 - T_2)}{T_1} \tag{51}$$

This equation demonstrates that the conversion of heat into work is never complete. In order to have a complete conversion of heat into work, the temperature of the heat sink must be equal to absolute zero. While it may be possible to bring a body of finite size close to absolute zero, it is entirely impossible to have at that temperature a heat sink or reservoir of infinite size, so that any transfer of a finite amount of heat will not increase the temperature of the heat sink. The temperature of the heat sink has to be maintained at the lower level. The work required to maintain a constant temperature for a heat sink of finite size can be as much as that obtained by the use of the lower temperature. The heat sink of finite size, therefore, has no use here in converting heat into work. The amount of heat which must be rejected to a heat sink is regarded as unavailable for producing work. From equation (46) the amount of unavailable energy Q_2 in a Carnot cycle is given by:

$$-Q_2 = \frac{Q_1 T_2}{T_1} = T_2 \, \Delta S_1 \tag{52}$$

where ΔS_1 is the increase in entropy of the fluid during the step of heat absorption. To generalize this situation, the heat can be absorbed by a working fluid while its temperature undergoes a continuous rise from T_1 to T_1'. The unavailable energy in this case will be similarly represented by:

$$-Q_2 = T_2 \int_{T_1}^{T_1'} \frac{\delta Q}{T} = T_2 \, \Delta S_1 \tag{53}$$

It can be seen that both equations (52) and (53) represent the same thing. Whenever heat is transferred by a fluid operating in a cyclic process for the purpose of producing work, part of the heat energy becomes unavailable for producing work, but this part is at a minimum in a reversible cycle. This minimum amount of unavailable energy is always equal to the product of the temperature of a heat sink of infinite capacity and the entropy change of the working fluid during its heat absorption. A practical heat sink of infinite size is the surrounding atmosphere. The sink temperature is of course the lowest natural temperature of the surroundings. In any actual process, which is always an irreversible one, the amount of heat energy made unavailable for producing work is greater than $T_2\ \Delta S_1$ for a reversible process.

In all actual processes a system is changed from a state of low probability to one of higher probability. The tendency of a system to pass from an orderly state into a random arrangement is a natural one. Entropy is a quantitative index of the probability or degree of randomness in the arrangement of a given system. A highly ordered arrangement is one of lower entropy, but, the higher the degree of randomness of a system, the larger is its entropy. When a system reaches a state of no randomness, its entropy becomes zero. By applying the theory of probability to molecular systems, the entropy of any such system can be related to the occurrence probability and the entropy values may be calculated on an absolute scale.

THE THIRD LAW OF THERMODYNAMICS (14,19)

The third law of thermodynamics was deduced from Nernst's heat theorem in conjunction with the application of quantum theory to heat capacity data of solids. The third law limits the entropy value of matter and puts the latter into an absolute scale. According to Nernst's heat theorem, the change in heat capacity, ΔC_p, during a chemical reaction decreases with decreasing temperature and approaches zero at the absolute zero of temperature. In other words, at absolute zero of temperature the heat capacity of reactants is identical with that of products. The heat theorem also states that the entropy change of a reaction involving solids approaches zero at the absolute zero temperature. All solids at the absolute zero temperature have identical values for entropy.

At constant pressure the difference in entropy of a substance between 0°K. and T°K. without phase change is obtained by substituting $C_p\ dT$ for δQ in equation (39) and integrating the resulting equation. Thus:

$$S_T - S_0 = \int_0^T \frac{C_p}{T}\, dT \tag{54}$$

In interpreting the heat capacity data of solids, the application of quantum theory has indicated that C_p/T should be either zero or a finite value as the temperature approaches the absolute zero. The entropy difference, $S_T - S_0$, in equation (54) is always positive. This means that at absolute zero of temperature a substance has the lowest possible entropy value.

If all substances have the same entropy at the absolute zero of temperature, and the entropy of a substance is at a minimum at the same temperature, it may be reasonable to assume that the entropy values are zero at 0°K. The entropy at any temperature T, according to equation (54) should be given by:

$$S_T = \int_0^T \frac{C_p\, dT}{T} \tag{55}$$

Planck first stated the third law in 1912. He suggested that the entropy approaches zero at 0°K. for pure solid and liquids. This generalization may not be true for liquids. A correct statement of the third law has been given as follows: Every substance has a finite positive entropy, but at the absolute zero of temperature the entropy may become zero, and does so in the case of a perfect crystalline substance.

To evaluate the absolute value of entropy S_T at any temperature, it is necessary to know the heat capacity data from that temperature down to zero. The improved low-temperature technique in recent years has made calorimetric measurement possible down to such low temperatures that it takes only a slight extrapolation to reach absolute zero. At very low temperatures the heat capacity for a monatomic solid is

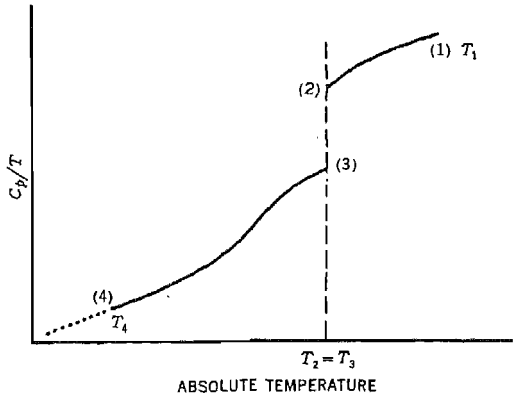


Fig. 5. Entropy determination by graphical integration.

proportional to the third power of the absolute temperature. This relation, known as Debye's equation of specific heat, is frequently used to guide such extrapolation. The integral in equation (55) is usually evaluated graphically. It involves the plot of C_p/T versus T, as indicated in Figure 5.

The curve between points (1) and (2) represents the plot of C_p/T for the liquid phase of a compound versus the temperature between T_1 and the melting point T_2 (or T_3). The curve between points (3) and (4) is a similar plot in the region of solid phase. Below point (4) the experimental heat capacity data are not available. Debye's equation of specific heat is used to extrapolate the curve from T_4 down to absolute zero. The break of the curve between points (2) and (3) is due to the occurrence of the melting point where the entropy of the system increases with no change in its temperature. The area under the whole curve from point (1) down to absolute zero plus the entropy change accompanying fusion gives the value of the entropy of the compound in the liquid phase at temperature T_1.

Entropy values evaluated on the basis of the third law may be used in conjunction with other thermochemical data to calculate the free-energy change of formation for various compounds. On comparing the value for the free energy of formation thus obtained with that obtained from other experimental data, such as chemical equilibrium data, the close agreement provides evidence in favor of the third law of thermodynamics.

Interrelations of Thermodynamic Functions

Free Energy and Work Function. In addition to internal energy and enthalpy, two more energy functions are used frequently in thermochemical calculations.

Under certain conditions of restraint they represent the energies capable of performing useful work. They are the Gibbs free energy, and the total work function (Helmholtz free energy).

Free energy, G, is defined in terms of enthalpy, temperature, and entropy, by the equation:

$$G = H - TS \tag{56}$$

Free energy is often represented by the symbol F. See "Nomenclature," p. 34.

In an isothermal process the change of the free energy of a system is:

$$\Delta G = \Delta H - \int_1^2 T\,dS \tag{57}$$

The change of enthalpy, ΔH, is related to the change of internal energy by:

$$\Delta H = \Delta U - \int_1^2 P\,dV - \int_1^2 V\,dP \tag{58}$$

Substituting the first-law expression into equation (58):

$$\Delta H = Q - W - \int_1^2 P\,dV - \int_1^2 V\,dP \tag{59}$$

The work term W in equation (59) can be broken down into two terms: mechanical work and available work other than mechanical work. The latter work can be designated W_f. The mechanical work is equal to $\int_1^2 P\,dV$, which can be cancelled out with the same term in equation (59).

By further limiting a process to a reversible one at constant pressure, Q becomes $\int_1^2 T\,dS$, and the $\int_1^2 V\,dP$ term drops out. Equation (59) finally takes the form:

$$\Delta H = \int_1^2 T\,dS - W_f \tag{60}$$

Substituting equation (60) into (57):

$$(\Delta G)_{P,T} = -W_f \tag{61}$$

Equation (61) indicates that the useful work obtained in a reversible and isothermal process under constant pressure is identical with the decrease in free energy of a system. Since the useful work obtained in an irreversible process is less than that in a reversible process, the free-energy decrease of a system represents the maximum amount of useful work which could be obtained in a constant-temperature and -pressure process.

Most ionic reactions can be carried out in an electrochemical cell to produce electrical energy. For example, the reaction between a copper sulfate solution and zinc can be conducted in an electrochemical cell containing a solution of copper sulfate with zinc as anode and a copper rod as cathode. The cell reaction is usually carried out at constant temperature and pressure. Through an external circuit, electric current will be produced as the chemical reaction proceeds. The useful work in this case is electrical work, equal to the product of the electromotive force and the quantity of electricity flowing through the external circuit. If a counterelectromotive force is applied in the external circuit infinitesimally smaller than that produced by the cell, the chemical reaction will take place in the cell reversibly. In this case the electrical work produced is at its maximum and is equal to the decrease of free energy of the reacting system.

Another useful thermodynamic energy function is *work function* or *total work function*, A. It is defined in terms of internal energy, temperature, and entropy:

$$A = U - TS \tag{62}$$

For an isothermal process the change in work function is:

$$\Delta A = \Delta U - \int_1^2 T\,dS \tag{63}$$

In applying the first law, equation (73) becomes

$$\Delta A = Q - W - \int_1^2 T\,dS \tag{64}$$

If a process is reversible, Q is identical with $\int_1^2 T\,dS$ and equation (74) is reduced to:

$$-\Delta A = W \tag{65}$$

The decrease of work function is therefore a measure of the maximum work produced by a system in an isothermal process. If the volume is maintained constant, the mechanical work is zero and the decrease of work function becomes the sole representation of the available or useful work which can be produced by a system.

Differential Energy Functions. For a closed system of constant composition, the differential thermodynamic energy can be expressed in terms of temperature, volume, pressure, and entropy. It starts with the first law of thermodynamics and uses the definitions of enthalpy, entropy, free energy, and work function. If the process is reversible, δQ in equation (7) is equal to $T\,dS$ according to the definition of entropy. δW is given by $P\,dV$ if the work produced is only mechanical. Thus the first-law expression for a closed system (equation 7), becomes:

$$dU = T\,dS - P\,dV \tag{66}$$

This is an expression for differential internal energy. When equation (66) is substituted into the definition of enthalpy in a differential form, the differential enthalpy expression is given by the equation:

$$dH = dU + P\,dV + V\,dp = T\,dS + V\,dP \tag{67}$$

Substituting equations (66) and (67) into (56) and (62), which define free energy and work function:

$$dG = dH - T\,dS - S\,dT = V\,dP - S\,dT \tag{68}$$

$$dA = dU - T\,dS - S\,dT = -P\,dV - S\,dT \tag{69}$$

Equations (66) through (69) are basic differential equations for the four energy functions: internal energy, enthalpy, free energy, and work function. All the terms in the equations are state functions, and the equations are generally applicable to a mass of matter of constant composition undergoing any physical change of state and are not restricted to a reversible process.

Maxwell Relations. The state functions of a system are single-valued functions, and their differentials are so-called exact differentials. The value of the integral of such a differential is dependent only upon the location of the terminal states irrespective of the path. It is a property of an exact differential involving several independent variables that the order of differentiation has no effect upon the value of a final derivative. For example:

$$\frac{\partial}{\partial V}\left(\frac{\partial U}{\partial S}\right)_V = \frac{\partial}{\partial S}\left(\frac{\partial U}{\partial V}\right)_S \tag{70}$$

$$\frac{\partial}{\partial P}\left(\frac{\partial h}{\partial S}\right)_P = \frac{\partial}{\partial S}\left(\frac{\partial h}{\partial P}\right)_S \tag{71}$$

$$\frac{\partial}{\partial V}\left(\frac{\partial A}{\partial T}\right)_V = \frac{\partial}{\partial T}\left(\frac{\partial A}{\partial V}\right)_T \tag{72}$$

$$\frac{\partial}{\partial T}\left(\frac{\partial G}{\partial P}\right)_T = \frac{\partial}{\partial P}\left(\frac{\partial G}{\partial T}\right)_P \tag{73}$$

Substituting equations (70) through (73) into the four expressions of differential energy functions:

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V \tag{74}$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P \tag{75}$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V \tag{76}$$

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P \tag{77}$$

These four equations are known as Maxwell relations. They are extremely useful in converting one group of variables, which are either not available or not measurable, into a group of variables readily available. For example, it is likely that the entropy data at different specific volumes cannot be determined directly and easily in an isothermal process. On the other hand, it is rather easy to obtain ordinary P-V-T data, and these are available in the literature for a considerable number of compounds and mixtures. Through equation (76) the rate of change of entropy with respect to volume in an isothermal process is identical with the rate of change of pressure with respect to temperature in a constant-volume process and can be thus calculated from the latter.

This interlocking connection of Maxwell relations has made it possible to develop a large variety of useful design data from a minimum amount of experimental data. They have proved a set of useful tools not only in process design and development but in research work as well.

The rigorous expression for the heat of transition is based upon equation (76), one of Maxwell's relations. For the vaporization of a liquid, the vapor pressure is independent of volume. The limitation of constant volume for the derivative on the right side of equation (76) can be dropped. When the vaporization is conducted at constant temperature, the entropy change must be equal to the ratio of heat of vaporization to the vaporization temperature. Thus:

$$\left(\frac{\partial S}{\partial V}\right)_T = \frac{\lambda}{T(V_v - V_l)} \tag{78}$$

where V_v, V_l are the vapor and liquid volume. Their difference represents the volume change of the system during the vaporization. Substituting equation (78) into (76) with the removal of the subscript of volume gives *Clapeyron's equation*:

$$\frac{dP}{dT} = \frac{\lambda}{T(V_v - V_l)} \tag{79}$$

Variation of Thermodynamic Properties with Process Conditions. Although a large number of thermodynamic properties are used in thermodynamic calculations, there are only three basic ones: specific volume, enthalpy, and entropy. Once these are known at different temperatures and pressures in different phases, all the other thermodynamic properties can be calculated. For example, it is possible to calculate free energy once the enthalpy and entropy data are given at a given temperature. Internal energy can be calculated from the values of enthalpy, pressure, and volume, and work function can be calculated from internal energy, entropy, and temperature. The Joule-Thomson coefficient can be obtained from data on enthalpy, temperature, and pressure.

Temperature and pressure are usually the operating variables in process plants. The effect of temperature and pressure upon the specific volumes of a system is determined experimentally, and the resulting data are known as the *P-V-T* data of the system. The *P-V-T* data for both vapor and liquid can be correlated through the compressibility and expansion factor (see *Calculations; Data; Density; Gases and vapors*) if the experimental values are not available.

In thermochemical calculations it becomes important to know the effect of pressure and temperature upon the entropy and enthalpy of the system. With the *P-V-T* data the enthalpy and entropy data at various pressures and temperatures can be used to establish all the other kinds of thermochemical data required in process design or development.

Enthalpy. Consider a system with two degrees of freedom. Its enthalpy must be a unique function of two variables, such as temperature and pressure. Thus:

$$H = f(P, T) \tag{80}$$

The system with two degrees of freedom represents a number of practical cases. A pure compound in a single-phase region, such as liquid or vapor phase, belongs to this category. If the composition of a mixture is fixed, the single-phase region also is a system with two degrees of freedom.

As temperature and pressure undergo change in a process, the enthalpy change of the system will be given by the expression:

$$\int_1^2 dH = \Delta H_1 = \int_{T_1}^{T_2} \left(\frac{\partial H_2}{\partial T}\right)_P dT + \int_{P_1}^{P_2} \left(\frac{\partial H}{\partial P}\right)_T dP \tag{81}$$

where T_1 and P_1 are the initial temperature and pressure, and T_2 and P_2 the final temperature and pressure of the system. In the conversion of a system from its initial state at T_1, P_1 to the final state, T_2, P_2, there are two alternative paths. Each path consists of two steps: isothermal and isobaric processes. Following path I of Figure 6, the system is first changed from the initial condition of T_1 and P_1 to T_1, P_2, the temperature being kept constant during this first step of the process. In the second step the pressure is kept constant at P_2 while the temperature is changed from T_1 to the final temperature T_2.

The increase of enthalpy in the first step, which is an isothermal process, is equal to

$$\int_{P_1}^{P_2} \left(\frac{\partial H}{\partial P}\right)_{T_1} dP$$

The enthalpy increase in the isobaric process, which follows the first step, is represented by

$$\int_{T_1}^{T_2} \left(\frac{\partial H}{\partial T}\right)_{P_1} dT$$

The summation of the enthalpy changes in these two steps gives the total change in enthalpy of the system along path I. Thus, with reference to paths I and II, equation

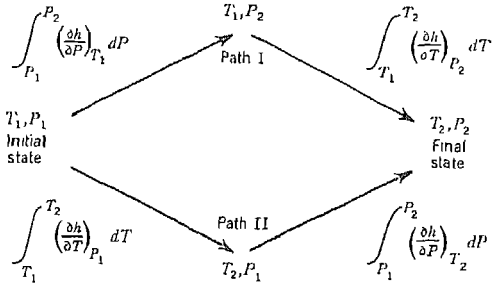


Fig. 6. Graphical representation for enthalpy change in a process.

(81) should be expressed more specifically with regard to the subscripts as follows:

Path I
$$\Delta H = \int_{P_1}^{P_2} \left(\frac{\partial H}{\partial P}\right)_{T_1} dP + \int_{T_1}^{T_2} \left(\frac{\partial H}{\partial T}\right)_{P_2} dT \tag{81a}$$

Path II
$$\Delta H = \int_{T_1}^{T_2} \left(\frac{\partial H}{\partial T}\right)_{P_1} dT + \int_{P_1}^{P_2} \left(\frac{\partial H}{\partial P}\right)_{T_2} dP \tag{81b}$$

Effect of Temperature upon Enthalpy. In substituting the definition of enthalpy into the first-law expression for a closed system, equation (7), the following equation is obtained if the work involved is limited to mechanical work:

$$dH = \delta Q + V\,dP \tag{82}$$

On differentiating equation (82) with respect to temperature by maintaining the pressure constant, the following relation between the partial derivative $(\partial H/\partial T)_P$ and heat capacity at constant pressure is obtained:

$$\left(\frac{\partial H}{\partial T}\right)_P = \left(\frac{\delta Q}{\partial T}\right)_P = C_p \tag{83}$$

Therefore, for a constant-pressure process, the change in enthalpy due to a change in temperature is given by:

$$\Delta H_p = \int_{T_1}^{T_2} C_p\,dT \tag{84}$$

C_p in equation (84) is the heat capacity at the pressure which is maintained constant in the process. The heat capacity data in the literature are usually those for the gases in the ideal gas state, as represented by C_p^*.

The heat capacity of a gas at any pressure and that of a liquid can be calculated from C_p^* with the relations to be developed in a later section (see p. 29). It is sufficient to state here that C_p of a gas at any pressure can be evaluated from that of an ideal gas if P-V-T data of the gas are available.

C_p^* for a monatomic gas is a constant equal to $5R/2$ B.t.u. per lb.-mole per degree Rankine. For the ideal gas of di- and other polyatomic molecules, C_p^* is usually a function of temperature. The exact form of the function is determined by the nature of the gas. For instance, the heat capacity data for carbon monoxide and steam are fitted well by a power function of temperature as follows:

$$C_p^* = \alpha + \beta t + \gamma t^2 + \ldots \tag{85}$$

The data for hydrogen are best fitted by:

$$C_p^* = \alpha + \beta t + \frac{\gamma}{t^2} \tag{86}$$

For carbon dioxide and oxygen, the best representation is:

$$C_p^* = \alpha + \beta t + \frac{\gamma}{\sqrt{t}} \tag{87}$$

In all three equations, α, β, and γ are numerical constants characteristic of the gas.

The heat capacity of an ideal solution is evaluated from the heat capacity and molar concentration of its components by a molar combination, as follows:

$$(C_p)_{\text{mixt.}} = \Sigma(C_p)_i X_i \tag{88}$$

where X_i is the mole fraction of the ith component. If the solution is nonideal, heat effect is involved during the mixing. Another datum required to evaluate the heat capacity of the mixture is the heat of mixing, usually known as heat of solution. Normally, if the experimental heat capacity data are not available for the mixture, its enthalpy is evaluated directly without these data, from the heat of mixing and the heat capacity data of its components by the method to be described in connection with the construction of an enthalpy-concentration diagram (see p 32).

Effect of Pressure upon Enthalpy. The expression giving the effect of pressure upon the enthalpy can be derived by differentiating equation (67). The resulting equation is:

$$\left(\frac{\partial H}{\partial P}\right)_T = T\left(\frac{\partial S}{\partial P}\right)_T + V \tag{89}$$

According to one of Maxwell's relations,

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P \tag{77}$$

equation (89) is transformed into:

$$\left(\frac{\partial H}{\partial P}\right)_T = V - T\left(\frac{\partial V}{\partial T}\right)_P \tag{90}$$

For a finite change of pressure at constant temperature the change of enthalpy can be evaluated by integrating equation (78):

$$\Delta H = \int_1^2 \partial H = \int_{P_1}^{P_2} \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] dP \tag{91}$$

It can be seen that the effect of pressure upon enthalpy can be determined if the P-V-T data of the system are available. If the P-V-T data can be fitted into an

equation, the integral in equation (91) can be solved by analytical differentiation followed by integration at constant temperature; otherwise graphical integration is used.

In the case of a gas, the *residual volume* is commonly used for graphical differentiation. Residual volume, represented by α', is the difference in volume between a real gas and an ideal gas. It is used to facilitate graphical differentiation and to eliminate mathematical uncertainty if one of the integration limits is at zero pressure. The residual volume is given by:

$$\alpha' = \frac{RT}{P} - V \tag{92}$$

Substituting equation (92) into (91):

$$\Delta H = \int_{P_1}^{P_2} \left[T \left(\frac{\partial \alpha'}{\partial T} \right)_P - \alpha' \right] dP \tag{93}$$

The integral in the equation is solved by graphical differentiation followed by graphical integration.

Entropy. By a treatment similar to that for enthalpy, the differential entropy change for a system with two degrees of freedom due to changes in temperature and pressure is given by:

$$dS = \left(\frac{\partial S}{\partial T} \right)_P dT + \left(\frac{\partial S}{\partial P} \right)_T dP \tag{94}$$

The effect of temperature and pressure upon the entropy of a system is expressed by either of the integrated forms of the fundamental differential equation:

$$\Delta S = \int_1^2 dS = \int_{T_1}^{T_2} \left(\frac{\partial S}{\partial T} \right)_{P_1} dT + \int_{P_1}^{P_2} \left(\frac{\partial S}{\partial P} \right)_{T_2} dP \tag{95}$$

or

$$\Delta S = \int_1^2 dS = \int_{T_1}^{T_2} \left(\frac{\partial S}{\partial T} \right)_{P_2} dT + \int_{P_1}^{P_2} \left(\frac{\partial S}{\partial P} \right)_{T_1} dP \tag{96}$$

In substituting the definition of entropy or δQ in equation (83), the following equation results for a reversible process:

$$\left(\frac{\partial S}{\partial T} \right)_P = \frac{C_p}{T} \tag{97}$$

Substitution of equation (95) and one of the Maxwell's relations, equation (77), into (95) and (96) leads to the working equation giving the effect of temperature and pressure upon the entropy:

$$\Delta S = \int_{T_1}^{T_2} \left(\frac{C_p}{T} \right)_{P_1} dT - \int_{P_1}^{P_2} \left[\left(\frac{\partial V}{\partial T} \right)_P \right]_{T_2} dP \tag{98}$$

or

$$\Delta S = \int_{T_1}^{T_2} \left(\frac{C_p}{T} \right)_{P_2} dT - \int_{P_1}^{P_2} \left[\left(\frac{\partial V}{\partial T} \right)_P \right]_{T_1} dP \tag{99}$$

The partial derivative $(\partial V/\partial T)_P$ in equation (98) or (99) should be evaluated under different pressures between the limits of P_1 to P_2 at one constant temperature.

Either graphical or analytical differentiation and integration can be used to evaluate both integrals in equations (98) and (99). Procedures similar to the treatment of enthalpy are used. If P-V-T data can be correlated in a convenient form of equation of state, and if heat capacity data are given as an analytical function of temperature, the analytical differentiation and integration are always preferable. Because of the difficulty mentioned previously, the second integral in equations (98) and (99) is graphically evaluated through the residual volume if graphical integration is adopted.

Heat Capacity. The effect of pressure upon the heat capacity of a pure compound or a mixture of given composition can be completely determined by the P-V-T data. The relation is developed from the differential expression for entropy change as given by equation (94). For an exact differential such as dS, the order of differentiation has no effect upon the value of a second derivative. Thus:

$$\left[\frac{\partial}{\partial P}\left(\frac{\partial S}{\partial T}\right)_P\right]_T = \left[\frac{\partial}{\partial T}\left(\frac{\partial S}{\partial P}\right)_T\right]_P \tag{100}$$

Substitution of equations (77) and (97) into (100) yields the differential expression giving the effect of pressure upon the heat capacity:

$$\left[\frac{\partial C_p}{\partial P}\right]_T = -\left[\frac{\partial}{\partial T}\left(\frac{\partial V}{\partial T}\right)_P\right]_P = -\left(\frac{\partial^2 V}{\partial T^2}\right)_P \tag{101}$$

The change of heat capacity due to the change of pressure is obtained by integrating equation (101):

$$(C_p)_{P_2} - (C_p)_{P_1} = -\int_{P_1}^{P_2}\left(\frac{\partial^2 V}{\partial T^2}\right)_P dP \tag{102}$$

It is seen that the right side of equation (102) contains only pressure, volume, and temperature as variables. Once the P-V-T data are available, the heat capacity of a system at one pressure can be calculated from that at another pressure. For most solids and liquids in the region well below the critical temperature, there is little effect of temperature upon the volume. According to equation (102), the heat capacity is affected little by pressure and is practically constant. The effect of temperature upon heat capacity has been discussed on p. 25. The temperature range covered by liquids is relatively narrow. The specific heat of liquids has about the same values, varying between 0.4 and 0.5 with a few exceptions. Water, ammonia, and methane have higher values, and mercury and chlorinated compounds have lower values. A power function of temperature up to the second power is sufficient to correlate the variations of heat capacity of liquids with temperature. In most cases a linear relation exists between heat capacity and temperature. The heat capacity of solids usually increases with rise of temperature. The maximum atomic heat capacity at constant volume is predicted to be $3R$, where R is the gas constant. The molar heat capacity of a compound is approximately equal to the summation of the atomic heat capacities of all its component atoms. This rule is known as Kopp's rule. For some light elements with atomic weight less than 40, the atomic heat capacities are somewhat smaller and vary in the range between 1.8 and 5.4 (14).

Relations between Various Heat Capacities. There are various heat capacities depending upon the restriction on a process. Heat capacity at constant pressure C_p is the amount of heat absorption per unit rise in temperature under constant pressure. For a constant-volume process, the heat capacity becomes heat capacity at constant volume, C_v. Heat capacity of a saturated vapor, C_{sv}, or of a saturated liquid (liquid in equilibrium with its vapor, that is, at its boiling point), C_{sl}, is the change of the enthalpy of a system per unit rise in temperature if saturation is maintained during a process. Mathematically, these terms are expressed as follows:

$$C_p = \left(\frac{\delta Q}{\partial T}\right)_P = T\left(\frac{\partial S}{\partial T}\right)_P \tag{103}$$

$$C_v = \left(\frac{\partial Q}{\partial T}\right)_V = T\left(\frac{\partial S}{\partial T}\right)_V \tag{104}$$

$$C_{sv} = \left(\frac{\partial h}{\partial T}\right)_{sv} \tag{105}$$

$$C_{sl} = \left(\frac{\partial h}{\partial T}\right)_{sl} \tag{106}$$

The entropy change for a system with two degrees of freedom is given by the following for a change in temperature and volume:

$$dS = \left(\frac{\partial S}{\partial T}\right)_V dT + \left(\frac{\partial S}{\partial V}\right)_T dV \tag{107}$$

The first partial derivative in equation (107) is related to C_v by equation (104). The second derivative is equal to $(\partial P/\partial T)_V$ according to one of Maxwell's relations, equation (76). Therefore, equation (107) can be transformed into:

$$dS = \frac{C_v}{T} dT + \left(\frac{\partial P}{\partial T}\right)_V dV \tag{108}$$

Similarly, the entropy change due to a differential change in temperature and pressure is given by the differential form of equation (98):

$$dS = \frac{C_p}{T} dT - \left(\frac{\partial V}{\partial T}\right)_P dP \tag{109}$$

Subtracting equation (109) from (108) gives:

$$C_p - C_v = T\left(\frac{\partial P}{\partial T}\right)_V \left(\frac{\partial V}{\partial T}\right)_P \tag{110}$$

The ratio of the two heat capacities can be derived by differentiating both equations (108) and (109) with respect to temperature by maintaining entropy constant. Thus:

$$C_v = -T\left(\frac{\partial V}{\partial T}\right)_S \left(\frac{\partial P}{\partial T}\right)_V \tag{111}$$

and

$$C_p = T\left(\frac{\partial P}{\partial T}\right)_S \left(\frac{\partial V}{\partial T}\right)_P \tag{112}$$

Dividing equation (112) by (111) gives the ratio of two heat capacities as follows:

$$\frac{C_p}{C_v} = -\left(\frac{\partial V}{\partial T}\right)_P \left(\frac{\partial T}{\partial P}\right)_V \left(\frac{\partial P}{\partial V}\right)_S \tag{113}$$

Heat Capacity of Saturated Phases (23). Consider a saturated vapor. The enthalpy change of the saturated phase due to the changes in temperature and pressure is given by equation (81). Further differentiating of the differential form of equation (81) with respect to temperature at saturation gives the relation between heat capacity of a saturated vapor and its heat capacity at constant pressure:

$$C_{sv} = (C_p)_v + \left(\frac{\partial H}{\partial P}\right)_T \left(\frac{dP}{dT}\right)_{sat} \tag{114}$$

In substituting equation (90) into (114), $(\partial H/\partial P)_T$ can be replaced with a function containing only P-V-T variables of the vapor. Thus:

$$C_{sv} = (C_p)_v + \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right]_V \left(\frac{dP}{dT}\right)_{sat} \tag{115}$$

$(dP/dT)_{sat}$ is the change of vapor pressure with respect to temperature increase, and it can be obtained directly from vapor pressure measurements. In the absence of vapor pressure data, $(dP/dT)_{sat}$ can be calculated by Clapeyron's equation, equation (79), provided the data of heat of vaporization and P-V-T of both liquid and vapor are available.

Similar treatment may be applied to the saturated liquid phase to give the relation between the heat capacity of a saturated vapor and its heat capacity at constant pressure. Thus:

$$(C_p)_l = C_{sl} + \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right]_l \left(\frac{dP}{dT}\right)_{sat} \tag{116}$$

A thermodynamic relation exists between the heat capacity of a saturated liquid and that of an ideal gas for the same system. This relation is derived by equating the enthalpy change along two alternative paths in converting a saturated liquid at a temperature T to a saturated vapor at a temperature $T + dT$. One path between the initial and final states is to heat the liquid at saturation to $T + dT$ and vaporize the saturated liquid at $T + dT$. The other is to vaporize the liquid at T and convert the saturated vapor formed isothermally to the ideal gas state by reducing the pressure to zero; the vapor in the ideal gas state is then heated to $T + dT$ and converted to the saturated vapor at $T + dT$ by an isothermal compression. The final relation between the heat capacities thus arrived at is:

$$C_{sl} - C_p^* = -\frac{d\lambda}{dT} - \frac{d(H^* - H)}{dT} \tag{117}$$

$d\lambda/dT$ is the change of heat of vaporization with respect to temperature. $(H^* - H)$ represents the difference in enthalpy between a real and an ideal gas at a temperature T and can be readily evaluated at different temperatures once the P-V-T data of the vapor are available.

The data on heat capacity of saturated liquid and vapor, and on constant-pressure heat capacity of compressed liquids, are generally not available. On the other hand,

the heat capacity data of an ideal gas can be determined more accurately from spectroscopic data by statistical mechanics. The existence of the rigorous relations between various heat capacities as represented by equations (115), (116), and (117) provides an avenue to evaluate those heat capacities which are difficult to determine.

Characterization of Complex Mixtures. All the preceding equations, (56) through (117), in this section, giving the interrelation of different thermodynamic properties, are applicable to mixtures of a given composition as well as to a pure compound. In the case of a complex mixture such as petroleum, it is impossible to identify all components present and to express the composition in an ordinary way. To account for the difference in the composition of petroleum, Watson and Nelson (14,31) proposed a term, "characterization factor":

$$K = \frac{(T_B)^{1/3}}{d_{60F}^{60F}} \tag{118}$$

where T_B is the molal average boiling point in degree Rankine determined from the A.S.T.M. distillation. The enthalpy of petroleum in both liquid and vapor phase have been given, in a graphical form, in terms of a function of characterization factor, API gravity, temperature, and pressure (3). Pseudo-critical constants of the petroleum, used in correlating the P-V-T data for such complex mixtures, have been given in terms of characterization factor and molecular weight (14,31).

Representation of Thermodynamic Properties

The orderly tabulation of thermodynamic properties is essential for the process design and performance prediction involving substances or mixtures over a wide range of operating conditions in both fluid and solid phase. For engineering practice, it has been found more convenient to have the essential thermodynamic properties presented in a graphical form known as a thermodynamic network or chart. Although a thermodynamic chart cannot retain the same accuracy as a table, it aids in visualizing the path of the process and saves considerable time in solving an engineering problem.

For a pure substance, the thermodynamic chart or table should consist of five essential properties: temperature, pressure, enthalpy, entropy, and volume. The latter three are extensive properties and are usually given on the basis of one pound of the substance. In the case of mixtures, the concentration terms become additional variables. The number of additional variables due to the concentration is equal to the number of components present minus one.

In the preparation of a thermodynamic network, which is normally given in two dimensions, the two most important properties are plotted along the principal coordinates as parameters; all the other properties are represented by various contour curves. For a pure compound, the state of which can be completely defined in terms of two properties, this two-dimensional representation is complete and satisfactory. For a mixture, a complete representation of all properties in one chart necessitates the use of a space model, which is not convenient. However, if a mixture of a constant composition is to be used, the chart can be given for each specific composition in the same way as for a pure compound. On the other hand, if the concentration of a mixture varies, as is the case in distillation, gas absorption, and so on, the concentration should be used as one of the principal coordinates. The enthalpy-concentration diagram is a thermodynamic chart in which the enthalpy of the mixture is plotted

against its concentration. In any single-phase region, liquid or vapor, the temperature and pressure are constructed as contour curves. For a moderate change in pressure, the chart constructed at an average pressure can be used for different pressures. In the two-phase region of the enthalpy concentration diagrams, tie lines are provided to give the compositions of liquid and vapor at equilibrium.

For a pure compound, or a mixture of constant composition, the following four types of thermodynamic charts are in frequent use: temperature-entropy, enthalpy-entropy (Mollier diagram), pressure-volume, temperature-enthalpy. Contour curves may be drawn on each of these charts for the other three properties. The selection of a chart depends upon the convenience in application. Once a thermodynamic chart of five properties is given, the other thermodynamic properties, such as internal energy, free energy, and work function, can be readily calculated.

In evaluating thermodynamic properties of a pure compound for the construction of a thermodynamic chart (11,14,23), the following experimental data covering the range of temperatures and pressure are required: vapor pressure; P-V-T data for both liquid and vapor; heat capacity data for the ideal gas state. If the values of entropy are to be given on the absolute scale, a value of absolute entropy is also required. Any supplementary or extra set of data, if available, can be used to check the consistency of the known data. For example, the data on Joule-Thomson coefficients can be used to check the consistency of heat capacity measurement. The measured value of heat of vaporization can be used to check the consistency between vapor pressures and P-V-T data of fluid phases.

The first step involved in the calculation of thermodynamic properties of a pure compound is to fit the experimental data with accurate equations. P-V-T data are preferably correlated by an equation of state giving the form as $V = f(P, T)$. Vapor pressure and heat capacity data are expressed as a function of temperature. This step will be essential if the analytical rather than the graphical method is used to evaluate thermodynamic properties.

Since the P-V-T data are given, the evaluation of thermodynamic properties for the construction of the chart amounts to the calculation of enthalpy and entropy at different temperatures and pressure in all the phases concerned. After the reference state has been selected for the enthalpy, the calculation always starts with the saturated liquid at the freezing point. The enthalpy and entropy of the saturated vapor at the freezing point are then calculated with the heat of vaporization, which in turn is calculated from the vapor pressure and specific volume data of both liquid and vapor by Clapeyron's equation. Since the vapor pressure at the freezing point is usually negligibly low, the vapor under this pressure is close to an ideal gas. With the heat capacity data of an ideal gas given, the entropy and enthalpy values at different temperatures at this same pressure can be readily calculated by equation (84), the integrated form of equation (97). Based upon the values calculated at this low pressure, the entropy and enthalpy values at the other high pressures can be computed with P-V-T data of the vapor along a number of isothermal paths by equation (91), the integrated form of equation (77). The limiting points along these isothermal curves are located by the vapor pressure data, the highest pressure for the vapor to exist at each temperature being its vapor pressure. The entropy and enthalpy values of the saturated liquid at different temperatures are calculated from those of saturated vapor with the heat of vaporization evaluated from Clapeyron's equation. With the P-V-T data for liquids, the enthalpy and entropy values of compressed liquids are

evaluated along a number of isothermal paths from those of saturated liquids at the same temperature in much the same way as for the vapor phase. These procedural steps are well illustrated by the arrowed paths in Figure 7.

The method (10,14) used in the construction of an enthalpy concentration diagram depends upon the kind of data available for the mixture. Consider a binary system with complete miscibility in the liquid phase. First choose a reference temperature (T_0) at which the enthalpy values of pure compounds are assigned zero. Next locate the two terminal points, the enthalpies of pure compounds, on the isothermal (T_1), where the heat of solution data are available. The relation used for the location of such terminal points is:

$$H(T_1) = \int_{T_0}^{T_1} (C_p)_1 \, dT \tag{119}$$

From the heat of solution data, the enthalpy of solution at T_1 is calculated for different concentrations by:

$$H(T_1) = X_A H_A + (1 - X_A) H_B - q_s \tag{120}$$

where X_A is mole fraction of compound A; H_A and H_B are the enthalpies of pure A and B at the temperature of the solution; q_s is the integral heat of solution per mole of solu-

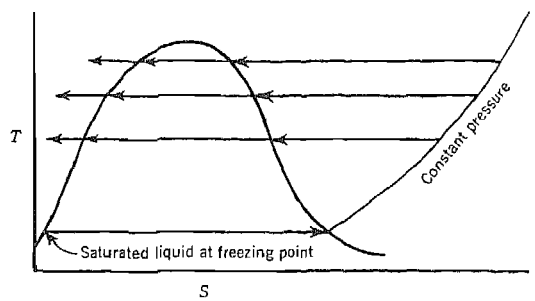


Fig. 7. Paths used in entropy and enthalpy evaluation.

tion. After the isotherm at T_1 is located, values on any other isotherms are evaluated from the equation:

$$H(T) = H(T_1) + \int_{T_1}^{T} (C_p)_{1X} \, dT \tag{121}$$

where $(C_p)_{1X}$ is the specific heat of solution at any concentration X. If the heats of solution at several temperatures instead of the specific heats of solution are available, locate several isotherms similarly with equation (120). Interpolation locates the other isotherms in the same phase.

If the liquid solution was formed from a salt (A) and water (B), the procedure would start with the location of the enthalpy values of pure water (H_B) by the method outlined previously. Next obtain the enthalpies of solutions at a given temperature by:

$$H_s = X_A q_\infty + (1 - X_A) H_B \tag{122}$$

Equation (122) was derived from the first law of thermodynamics by choosing infinite dilution as the reference state for the salt (B) where the enthalpy of the latter is assigned zero. The term q_∞ in equation (122) refers to the heat of dilution at infinite

dilution, which is evaluated by extrapolating the heat of solution data to the zero concentration of the salt.

With the availability of the data for heat of vaporization, vapor-liquid equilibrium, and specific heat of vapor, the construction of an enthalpy-concentration diagram can be extended into the two-phase and superheated vapor phase regions. The saturated liquid curve is the locus of the points of intersection of the isotherms and the vertical lines for the compositions relating the temperatures by the bubble point data. By adding the heat of vaporization of the pure components to the values of enthalpy at the two ends of the curve for saturated liquid, the points giving the enthalpy of vapor of two pure compounds are located. Other points in the saturated vapor curve are similarly located with the data for heat of vaporization of the mixture at various compositions. A more convenient method to locate the saturation vapor curve is to use the intersection of the isotherms in the superheated vapor phase and the vertical line for the compositions at the various dew points. The isotherms in the vapor region are straight lines connecting the points for the enthalpy of pure compounds, because the heat of mixing the gases is negligibly small.

Correlation and Prediction of Thermodynamic Data

The lack of either part or all of the thermodynamic data has often constituted a serious problem in process design. It happens very often that the collection of experimental data appears to be impossible, or at least impractical, as far as a process engineer is concerned.

Various methods of correlation are now available to chemical engineers for computing additional data in a given range from the somewhat incomplete given data. Correlations developed from rigorous principles of thermodynamics not only create confidence in the interpolation of the data, but also give critical tests for the consistency of existing experimental data. Wherever possible, a good design engineer should always test design data, before using them, by the thermodynamic correlations. See *Data* (*correlation*); *Vapor pressure*; and references 1,3,8,10–17,23,28,31–34,37–54,57,62,65–67,72.

Frequently it happens that the thermodynamic data required for the design are completely lacking. In such cases, the successful solution of a problem depends a great deal upon the ability of an engineer to "predict" thermodynamic data, that is, to calculate their probable values from extremely meager, apparently unrelated pieces of information. The basic data required for the complete evaluation of various thermodynamic data are: (*1*) vapor pressure; (*2*) *P-V-T* data of liquid and vapor phase; (*3*) heat capacity in the ideal gas state; (*4*) entropy value at any given state; (*5*) heat of reaction at any given condition; (*6*) heat of solution or dilution. There is no method available at present for such prediction of vapor pressure data, although, if the boiling point is known, it is possible to make an estimate of the critical properties (23,34), and thence of the vapor pressure data, by the use of the Othmer plot, Antoine equation, or Cox chart. *P-V-T* data for the vapor can be predicted either from the generalized compressibility factor (5a,14,23) or from generalized equations of state (67). Although a generalized correlation through the compressibility factor has been similarly proposed (32) for saturated liquids, the use of the expansion factor is considered to be a method applicable to both saturated and compressed liquids (23). These generalized correlations for both liquid and vapor can lead to the prediction of *P-V-T*

data from the critical properties, if these are known, or even if they themselves have been predicted by Meissner's method from the chemical formula of the substance (34). Heat capacity data in ideal gas state can be predicted for both hydrocarbons and non-hydrocarbons from their structural formula (14,23,65). With various methods available, it is always advisable to use more than one method in the prediction of heat capacity data for the purpose of cross-checking. Statistical as well as empirical methods have been used to develop the equations for the computation of entropy (15,23,66,72). Data on heat of reactions can be predicted from bond energy (28,56), group contribution (23), or a semi-empirical method for hydrocarbons only (66). For the heat of solution, there are available only methods of limited validity (1,21,64). Predictions of heat of vaporization and liquid heat capacity from the structural formulas of compounds are given in the literature (6,8).

In processing the complex thermodynamic calculation, the use of I.B.M. machines is recommended (63). It may be worth while to point out that there is no excuse for using the method of prediction if the experimental data are available in the literature. Of all the methods of prediction discussed, very few are not empirical in nature.

Nomenclature

The choice of symbols used in thermodynamics has suffered from an unfortunate lack of uniformity. The nomenclature used here is based on that recommended by the American Institute of Chemical Engineers (5a). Among other scientists in the U.S. the symbol F is widely used for free energy (Gibbs), but the American Institute of Chemical Engineers recommends G, which does not lead to confusion with the Faraday constant F. In Europe also G is widely used for the Gibbs free energy, and F often denotes the Helmholtz free energy (total work function), which is represented in the U.S. by A.

A	area of cross section
	total work function
C	number of components
C_p, C_v	heat capacity at constant pressure or volume
D	diameter
f	friction factor
	function
F	force
	degrees of freedom
F'	frictional loss
g_c	dimensional constant in Newton's law, g_c = (mass)(acceleration)/force
G	free energy
H	enthalpy
K	characterization factor
L	length
m	mass
M	molecular weight
N	number in general
	total number of moles
P	pressure
	number of phases
P_e	external pressure
q	heat flux
	rate of heat transfer per unit area of heat transfer surface
q_s	integral heat of solution per mole of solution

q_∞ heat of solution at infinite dilution
Q heat absorbed by a system
R gas constant
S entropy
T absolute temperature
T_B normal boiling temperature
u velocity
U internal energy
V volume
w mass flow rate
W work; work done by a system
W_f available work other than mechanical work of expansion
X height
mole fraction; species is denoted by subscript
Z compressibility factor

Differentials

d differential amount independent of path
δ differential amount dependent on path
∂ partial differential
Δ finite difference

Greek Letters

α, β, γ, etc. constants
α' residual volume
λ heat of vaporization

Subscripts

1 initial state, or step 1
2 final state or step 2
3, 4, etc. steps 3, 4, etc.
A, B, . . ., I designations of compounds
i inside, as D_i, inside diameter
generalized designation by number of a compound
l liquid
m mean value
P products
R reactants
sat saturated
sl saturated liquid (in equilibrium with saturated vapor)
sv saturated vapor
v vapor
∞ infinite dilution

Superscripts

* ideal state
0 standard state

Bibliography

(1) American Institute of Chemical Engineers, *Applied Thermodynamics*, Chemical Engineering Progress Symposium Series No. 7, New York, 1953.
(2) American Petroleum Institute, Research Project 44, *Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds*, Carnegie Press, Pittsburgh, Pa., 1953.
(3) Bauer, C. R., and Middleton, J. F., *Petroleum Refiner*, **32**, 111 (1953).
(4) Bichowsky, F. G., and Moskow, F. D., *The Thermochemistry of the Chemical Substances*, Reinhold, N.Y., 1936.

(5) Bosnjakovic, F., *Technische Thermodynamik*, Steinkopff, Dresden, 1948.
(5a) *Chem. Eng. Progr.*, **51**, 1955. In press.
(6) Chow, W. M., and Bright, J. A., Jr., *Chem. Eng. Progr.*, **49**, 175 (1953).
(7) Chu, J. C., Brooks, R. F., Wang, S. L., and Kharbanda, O. P., *Ind. Eng. Chem.*, **46**, 754 (1951).
(8) Chu, J. C., Dmytryszyn, M., Moder, J. J., and Overbeck, R. L., *Ind. Eng. Chem.*, **41**, 131 (1949).
(9) Chu, J. C., Getty, R., Brennecke, L., and Paul, R., *Distillation Equilibrium Data*, Reinhold, N.Y., 1950.
(10) Chu, J. C., and Hsu, K. S., *Chem. Inds.*, **64**, 454 (1949).
(11) Chu, J. C., Mueller, N. F., Busche, R. M., Jenny, A. S., *Petroleum Processing*, **5**, 1202 (1950).
(12) Chu, J. C., and Yang, W. J., *Ind. Eng. Chem.*, **42**, 373 (1950).
(13) Coates, J., and Sakiadis, B. C., *Louisiana State Univ. Eng. Expt. Sta. Bull.*, **34** (1953).
(14) Dodge, B. F., *Chemical Engineering Thermodynamics*, McGraw-Hill, N.Y., 1944.
(15) Dreisbach, R. R., and Spencer, R. S., *Ind. Eng. Chem.*, **41**, 1363 (1949).
(16) Edmister, W. C., "Application of Thermodynamics to Hydrocarbon Processing" (in 24 parts), *Petroleum Refiner*, **26**, No. 7, 77–82 (1947) to **28**, No. 11, 149–155 (1949).
(17) Franklin, J. L., *Ind. Eng. Chem.*, **41**, 1070 (1949).
(18) "Freon," Kinetic Chemicals, Inc., Wilmington, Del., 1945.
(19) Glasstone, S., *Thermodynamics for Chemists*, Van Nostrand, N.Y., 1947.
(20) Hawkins, G. A., and Smith, J. M., *Purdue Univ. Eng. Bull. Research Ser.*, **108** (1949).
(21) Hildebrand, J. H., and Scott, R. L., *Solubility of Non-electrolytes*, Reinhold, N.Y., 1950.
(22) Hottel, H. C., Williams, G. C., and Satterfield, C. N., *Thermodynamic Charts for Combustion Processes*, Wiley, N.Y., 1949.
(23) Hougen, O. A., and Watson, K. M., *Thermodynamics*, Wiley, N.Y., 1947.
(24) Justi, E., *Spezifische Wärme, Enthalpie, Entropie und Dissoziation Technischer Gase*, Springer, Berlin, 1938.
(25) Keenan, J. H., *Thermodynamics*, Wiley, N.Y., 1941.
(26) Keenan, J. H., and Keyes, F. G., *Thermodynamic Properties of Steam*, Wiley, N.Y., 1936.
(27) Keenan, J. H., and Keyes, F. G., *Gas Tables. Thermodynamic Properties of Air, Products of Combustion and Component Gases, and Compressible Flow Functions*, Wiley, N.Y., 1948.
(27a) Kiefer, P. J., Kinney, G. F., and Stuart, M. C., *Principles of Engineering Thermodynamics*, Wiley, N.Y., 1954.
(28) Klotz, I. M., *Chemical Thermodynamics*, Prentice-Hall, N.Y., 1950.
(29) Kobe, K. A., *et al.*, *Thermochemistry for the Petrochemical Industry*, Petroleum Refiner, N.Y., 1949–51.
(30) Lewis, G. N., and Randall, M., *Thermodynamics and the Free Energy of Chemical Substances*, McGraw-Hill, N.Y., 1923.
(31) Maxwell, J. D., *Data Book of Hydrocarbons*, Van Nostrand, N.Y., 1951.
(32) Meissner, H. P., *Ind. Eng. Chem.*, **33**, 1189 (1941).
(33) Meissner, H. P., *Ind. Eng. Chem.*, **40**, 904 (1948).
(34) Meissner, H. P., *Ind. Eng. Chem.*, **34**, 521 (1942).
(35) Meissner, H. P., *Chem. Eng. Progr.*, **45**, 149 (1949).
(36) Othmer, D. F., *Ind. Eng. Chem.*, **28**, 1435 (1936).
(37) Othmer, D. F., *Ind. Eng. Chem.*, **32**, 841 (1940).
(38) Othmer, D. F., *Chem. Met. Eng.*, **47**, 296 (1940).
(39) Othmer, D. F., *Chem. Met. Eng.*, **47**, 551, 631 (1940).
(40) Othmer, D. F., *Ind. Eng. Chem.*, **34**, 1072 (1942).
(41) Othmer, D. F., *Ind. Eng. Chem.*, **36**, 669 (1944).
(42) Othmer, D. F., *Proc. XIth Intern. Congr. Pure and Appl. Chem.*, London, 1953.
(43) Othmer, D. F., and Beattie, R. D., *Petroleum Refiner*, **31**, 129 (1952).
(44) Othmer, D. F., and Conwell, J. W., *Ind. Eng. Chem.*, **37**, 1112 (1945).
(45) Othmer, D. F., and Gilmont, R., *Ind. Eng. Chem.*, **36**, 858 (1944).
(46) Othmer, D. F., and Gilmont, R., *Ind. Eng. Chem.*, **40**, 2118 (1948).
(47) Othmer, D. F., and Josefowitz, S., *Ind. Eng. Chem.*, **38**, 111 (1946).
(48) Othmer, D. F., Josefowitz, S., and Schmutzler, A., *Ind. Eng. Chem.*, **40**, 886 (1948).
(49) Othmer, D. F., Josefowitz, S., and Schmutzler, A., *Ind. Eng. Chem.*, **40**, 833 (1948).
(50) Othmer, D. F., and Luley, A. H., *Ind. Eng. Chem.*, **38**, 408 (1946).
(51) Othmer, D. F., Ricciardi, L. G., and Thakar, M. S., *Ind. Eng. Chem.*, **45**, 1815 (1953).
(52) Othmer, D. F., and Sawyer, F. G., *Ind. Eng. Chem.*, **35**, 1269 (1943).

(53) Othmer, D. F., and Thaker, M. S., *Ind. Eng. Chem.*, **44**, 1654 (1952).
(54) Othmer, D. F., and White, R. E., *Ind. Eng. Chem.*, **34**, 952 (1942).
(55) Parks, G. S., and Huffman, H. M., *The Free Energies of Some Organic Compounds*, Reinhold, N.Y., 1932.
(56) Paul, M. A., *Principles of Thermodynamics*, McGraw-Hill, N.Y., 1951.
(57) Pauling, L., *Nature of the Chemical Bond*, Cornell Univ. Press, Ithaca, N.Y., 1940.
(58) Rossini, F. D., *et al.*, "Selected Values of Chemical Thermodynamic Properties," *Natl. Bur. Standards (U.S.) Circ.*, **500** (1950).
(59) Rossini, F. D., *Chemical Thermodynamics*, Wiley, N.Y., 1950.
(60) Sage, B. H., and Lacey, W. N., *Thermodynamic Properties of the Lighter Paraffin Hydrocarbons and Nitrogen*, American Petroleum Inst., N.Y., 1950.
(61) Sage, B. H., and Lacey, W. N., *Volumetric and Phase Behavior of Hydrocarbons*, Stanford Univ. Press, Stanford, Calif., 1950.
(62) Sawyer, F. G., and Othmer, D. F., *Ind. Eng. Chem.*, **36**, 894 (1944).
(63) Sherman, J., "The Use of IBM Machines in Thermodynamic Computations," presented at Am. Inst. Chem. Engrs., meeting, Washington, D.C., March 1954.
(64) Smith, J. M., *Introduction to Chemical Engineering Thermodynamics*, McGraw-Hill, N.Y., 1949.
(65) Souders, M., Jr., Matthews, C. S., and Hurd, C. O., *Ind. Eng. Chem.*, **41**, 1037 (1949).
(66) Souders, M., Jr., Matthews, C. S., and Hurd, C. O., *Ind. Eng. Chem.*, **41**, 1048 (1949).
(67) Su, G. J., and Chang, C. H., *J. Am. Chem. Soc.*, **68**, 1080 (1946); *Ind. Eng. Chem.*, **38**, 800 (1946).
(68) Tsao, C. C., and Smith, J. M., "Heats of Mixing of Liquids," in *Applied Thermodynamics*, Am. Inst. Chem. Engrs. Symposium Ser., Vol. **49**, No. 7, 107 (1953).
(69) *U.S. Bur. Mines Bull.*, **142** (1923); **407** (1937); **434** (1941).
(70) Weber, H. C., *Thermodynamics for Chemical Engineers*, Wiley, N.Y., 1939.
(71) Weibke, F., and Kubaschewski, O., *Thermochemie der Legierungen*, Springer, Berlin, 1943.
(72) Wenner, R. R., *Thermodynamical Calculation*, McGraw-Hill, N.Y., 1941.

JU CHIN CHU

THERMOFOR PROCESS. See *Petroleum (refinery processes)*, Vol. **10**, p. 131.

THERMOMETRY. See *Electronics*, Vol. **5**, p. 592; *Temperature measurement.*

THERMOPLASTICS; THERMOSETTING PLASTICS. See *Plastics*, Vol. **10**, pp. 798–799.

THERMOPSINE, $C_{15}H_{20}N_2O$. See *Alkaloids*, Vol. **1**, p. 483.

THETINS, $R_2S.O.CO.CH_2$. See *Sulfur compounds, organic*, Vol. **13**, p. 442.

THEVETIN; THEVETIGENIN, $C_{23}H_{33}O_4$. See *Cardiovascular agents*, Vol. **3**, p. 214.

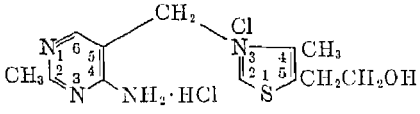
THIA-

For names of heterocyclic compounds derived from names of carbocyclic compounds by prefixing thia- to denote replacement of ring carbon by sulfur (such as "1-thiaindene" and "thiamorpholine") see under *Heterocyclic compounds.* See also *Sulfides, organic*, Vol. **13**, p. 295.

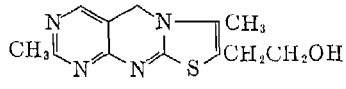
THIALS, RCHS. See *Sulfur compounds, organic*, Vol. **13**, p. 442.

THIAMINE

Thiamine (thiamin, vitamin B_1, thiamine chloride, 3-(4-amino-2-methyl-5-pyrimidinylmethyl)-5-(2-hydroxyethyl)-4-methylthiazolium chloride), $C_{12}H_{17}ClN_4OS$; formula weight 301.18, is a member of the vitamin B complex group (see *Vitamins*). A deficiency of thiamine in the diet may lead to a deterioration of the nervous system. Thiamine hydrochloride(I), U.S.P. XIV, N.N.R., is the usual form of the vitamin. The mononitrate salt of the thiazolium cation (thiamine mononitrate, U.S.P. XIV) is also on the market. The names thiamine and vitamin B_1 have been used ambiguously; thus the salt represented in formula (I) has been called thiamine chloride hydrochloride, thiamine hydrochloride and vitamin B_1 hydrochloride, thiamine and vitamin B_1. Whenever this salt is specifically referred to in this article, it will be called thiamine hydrochloride. (The positions in the pyrimidine ring are often distinguished by primes.)



(I) Thiamine hydrochloride



(II) Thiochrome

Vitamin B_1 occurs in nature in the form of its salts, esters with phosphoric acids, or as a pyrophosphoric acid ester–protein–metal complex (carboxylase). It is present in high concentrations in seeds, and in small amounts it is widely distributed in the animal organism in different organs and muscles. The vitamin is available commercially in bulk form as the hydrochloride or the mononitrate for use in food enrichment or the compounding of pharmaceutical forms. Only the hydrochloride is used for the preparation of solutions for injection.

In 1884 Takaki, when he checked the onslaught of beriberi in the Japanese Navy, demonstrated that it is a deficiency disease by changing the staple of the diet from polished to unpolished rice. In 1912 Funk cured rats of dietary polyneuritis by the administration of extracts of rice bran, and in 1926 Jansen and Donath isolated vitamin B_1 in crystalline form from rice bran. The structure of thiamine was elucidated independently in 1936 by teams led by Williams and by Grewe, and later in the same year syntheses were reported by the Williams group in the U.S. and by Andersag and Westphal in Germany. It was soon established that thiamine in the form of its pyrophosphoric acid ester (cocarboxylase) played an important role in human nutrition as a part of the enzyme systems catalyzing the decarboxylation of α-keto acids (such as pyruvic acid, $CH_3COCOOH$). Utilization of the vitamin has increased steadily until today more than 125 tons of the vitamin are synthesized annually for the treatment or prevention of thiamine deficiency.

Physical and Chemical Properties

The basic thiamine nucleus is a cation, which forms salts with many acids, the center(s) of basicity being the quaternary nitrogen in the thiazole ring alone or that nitrogen plus the primary amino group attached to the pyrimidine ring. Whereas a multitude of salts has been reported, the hydrochloride and the mononitrate have been used most widely.

As might be anticipated from the presence of the pyrimidine and thiazole rings, thiamine salts exhibit an absorption in the ultraviolet region; the maxima are at 235

and 267 mμ (44). Absorption data proved of considerable value in the elucidation of the structure of thiamine, but there has been little application of this technique for analytical purposes.

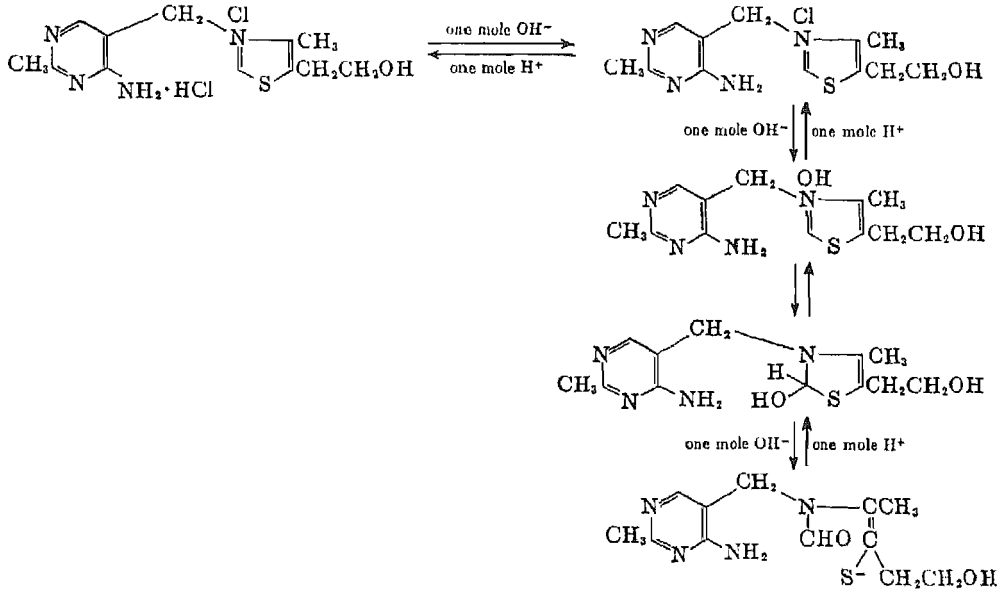
Thiamine salts can undergo the characteristic reactions of a primary amino group and a primary alcohol group, and these reactions were also of value in the work on structure. Many of the early observations, for example the vulnerability of thiamine to degradation by nitrite and acetates, are now interpreted as the loss of the amino group in the 4-position of the pyrimidine ring or the general instability of thiamine at an elevated pH.

Thiamine salts are easily oxidized by a variety of oxidizing agents, even air, to the biologically inactive *thiochrome* (II); this fact has been utilized in the "thiochrome assay" (see p. 40). Thiochrome has been synthesized by Todd and co-workers (31) using an approach quite similar to one of the thiamine syntheses.

Thiamine is reported to be easily reduced to a dihydro form (18), which is biologically inactive. The reaction is irreversible.

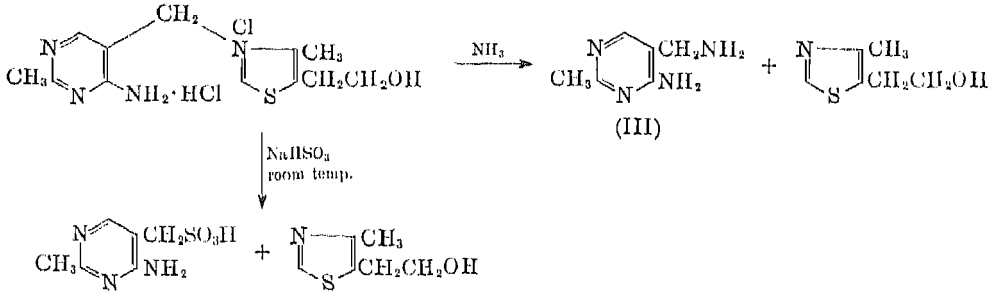
Thiamine hydrochloride is a white, crystalline solid, m.p. approx. 248°C. (decompn.). It is thermally stable at temperatures as high as 100°C. for long periods. Its solubility in water is high, 1 g./1 ml.; in 95% ethyl alcohol, 1 g./100 ml.; in absolute ethyl alcohol, 1 g./315 ml. Thiamine hydrochloride is essentially insoluble in all nonpolar solvents. The material is mildly hygroscopic, absorbing an amount of water equivalent to about 5% of its weight from air of average humidity; the hydrated material is easily desiccated at 100°C. Aqueous solutions of thiamine hydrochloride are acidic; the pH of a 1% wt./vol. solution is 3.13. Aqueous solutions in the pH range 3 to 5.5 are reasonably stable toward thermal sterilization at 120°C. There is a marked decrease in stability as solutions are made progressively more alkaline, and above a pH of about 7, corresponding to the univalent cation, thiamine is regarded as an unstable compound. The changes occurring upon the titration of thiamine hydrochloride with alkali have been reported by Williams and Spies (see Scheme 1).

SCHEME 1



Thiamine hydrochloride decomposes when treated with sulfite solutions (43) or liquid ammonia, producing among other products 2-methyl-4-amino-5-(aminomethyl)pyrimidine (III), (8,40) (see Scheme 2). These reactions helped determine the structure of the pyrimidine ring and the mode of attachment of the pyrimidine and thiazole rings.

SCHEME 2



Thiamine mononitrate is a white, crystalline solid, m.p. 196–200°C. (decompn.). The solubility in water is about 1 g./37 ml. at 25°C. and 1 g./3.4 ml. at 100°C. Aqueous solutions are essentially neutral. Since the thermal stability of the mononitrate is significantly greater than that of the hydrochloride, the former is used frequently in preference to the hydrochloride in the fortification of cereal products which are to be cooked.

Assay Methods

Thiamine may be assayed by fluorometric, gravimetric, colorimetric (13, Vol. I, pp. 217–223), microbiological (13, Vol. I, pp. 372–377), and animal (13, Vol. II, pp. 179–201) assay methods. Of these, the fluorometric procedures have attained the widest acceptance (2;13, Vol. II, pp. 92–102). These involve oxidation of thiamine to the highly fluorescent thiochrome (II); the fluorescence is then compared with that from a standard thiamine solution. This is the U.S.P. assay procedure. One gram of the vitamin is equivalent to 333,000 international units.

Occurrence

Thiamine is found in practically all animal and plant tissue in widely varying amounts. In plants the only significant concentration is in the seeds. Although there is no large storage in animals, the concentrations of thiamine in the liver, kidneys, and muscular tissue (particularly the heart) are higher than in other parts of the body. The thiamine may occur as a salt, as the pyrophosphoric acid ester (cocarboxylase), as the triphosphoric acid ester or as complexes with protein and phosphoric acid.

Since natural sources are not adequate for economical isolation of thiamine, all of the thiamine of commerce is produced synthetically.

Dietary Sources of Thiamine. All forms of life require thiamine, and all forms of plants and several animals are capable of synthesizing the vitamin in quantities at least adequate for survival. The ruminants, such as sheep (22) and cattle (3,36), synthesize the thiamine they need by bacterial action in the rumen. It is for this

reason that a significant role has never been found for thiamine in animal husbandry. On the other hand, thiamine deficiency characteristics not unlike those observed in humans can be induced in pigeons, rats, and mice by using controlled diets, demonstrating that these animals cannot synthesize the amount of thiamine necessary for healthy maintenance and must obtain their supply of the vitamin through their diets.

The thiamine contents of several foods are given (33) in Table I (see also *Cottonseed*; *Fish and shellfish*). Although these sources are of great importance nutritionally, significant proportions of the vitamin are destroyed in conventional cooking processes. There appears to be an anomaly between the stability of pure thiamine and moderate instability upon cooking. However, practically all foods are prepared at an essentially neutral pH, that is, considerably above the pH required for optimum stability of thiamine. Furthermore, heavy metals, which may be dissolved from the cooking vessel or are present in the water, and several diverse reactive organic groups detract substantially from the stability of the molecule. Therefore, it is common practice to supplement the naturally occurring thiamine in cereals with the pure vitamin, thus compensating for losses incurred in processing and cooking and insuring a reasonably adequate thiamine intake.

TABLE I. Dietary Sources of Thiamine.

Food	μg./100 g.	Food	μg./100 g.
Wheat germ	2050	Flour, rye, whole grain	470
Soy flour	770–1100	Wheat, whole grain	450
Pork, various cuts	620–1050	Corn meal, whole grain	410–450
Peas, split	870	Milk, dry skim	350
Pecans	720	Milk, dry whole	300
Oatmeal	550	Rice, brown	290
Heart, fresh	540	Bread, whole wheat	280

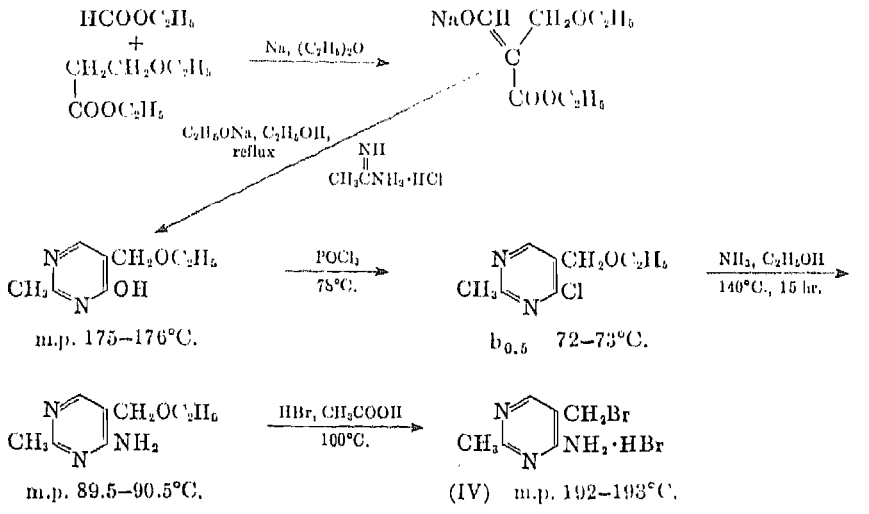
Source: Refs. (32) and (33).

Synthesis

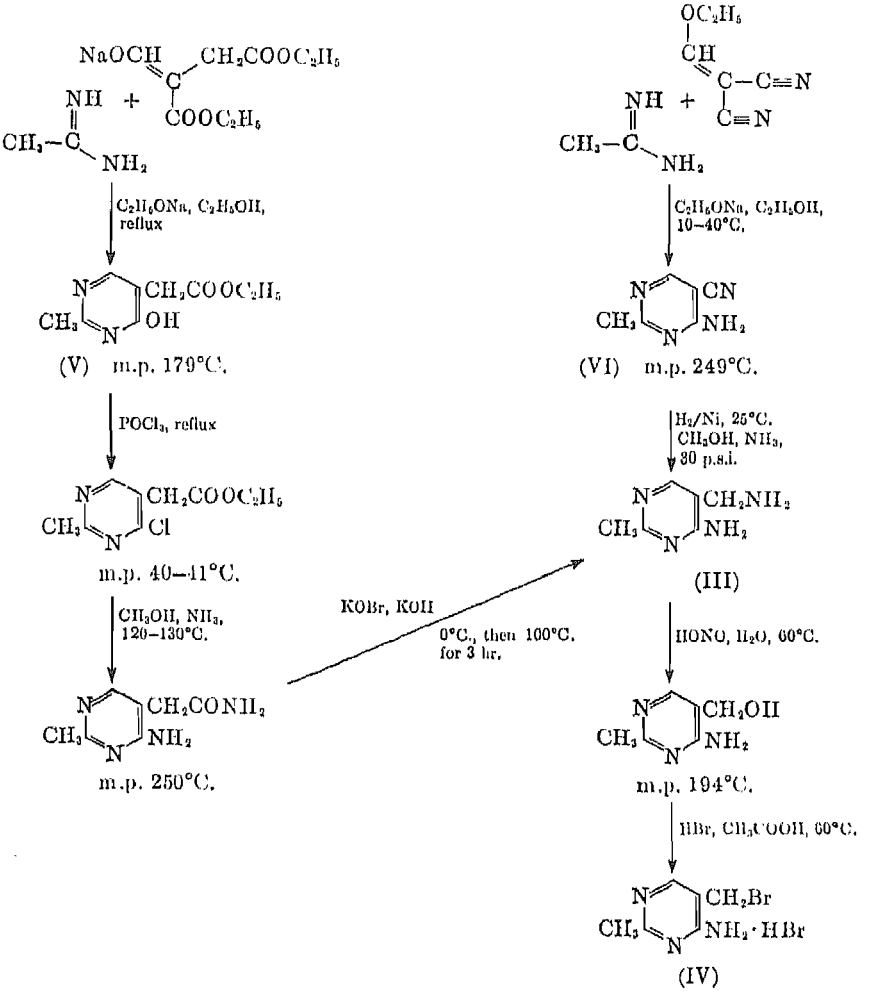
The structure of thiamine (I, shown as the hydrochloride), consisting of a substituted pyrimidine and a substituted thiazole moiety linked together by a methylene bridge, was proposed by Williams in 1936 (40), and soon thereafter was established by synthesis. All methods for the synthesis of thiamine start either with both the substituted pyrimidine and thiazole rings or with one of the two. There are several possible syntheses of the **pyrimidine** moiety (2-methyl-4-amino-5-(bromomethyl)-pyrimidine hydrobromide (IV)). One synthesis starts with ethyl formate, ethyl 3-ethoxypropionate and acetamidine (7) (see Scheme 3). Alternate pyrimidine syntheses with either the 5-(carbethoxymethyl)pyrimidine (5-(ethoxycarbonylmethyl)-pyrimidine (*C.A.*) (V)) (1) or the 5-cyanopyrimidine (VI) (12) as the first cyclic intermediate are shown in Scheme 4. These syntheses may be carried through to (IV) or terminated with the 5-(aminomethyl)pyrimidine (III), which is isolated as the dihydrochloride, m.p. 270°C. (decompn.).

The syntheses of the **thiazole** moiety (4-methyl-5-(2-hydroxyethyl)thiazole, 4-methyl-5-thiazoleethanol (*C.A.*) (VIII)) have usually been based on the reaction of thioformamide with γ-acetyl-γ-chloropropanol (3-chloro-5-hydroxy-2-pentanone (*C.A.*) (VII)) or its equivalent (see Scheme 5 (5)). Clarke and Gurin (6) used the ethyl ether of (VII), and Todd *et al.* (30) used esters. The use of thioformamide has been

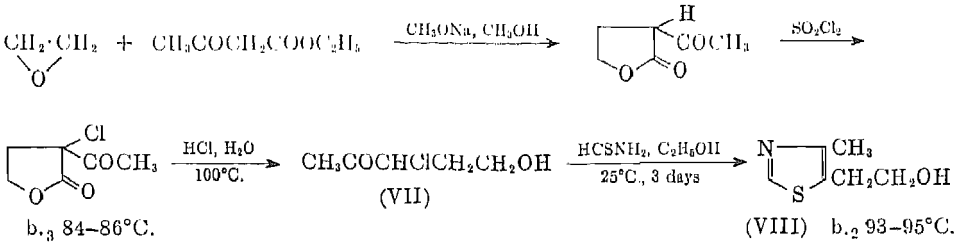
SCHEME 3



SCHEME 4



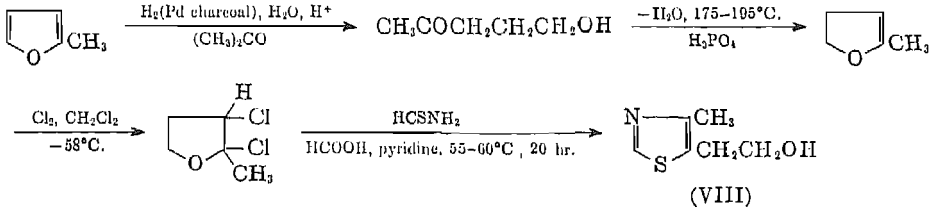
SCHEME 5



avoided by the deamination (14) or desulfurization (47) of the 2-amino or 2-mercapto derivative of (VIII).

Derivatives of furfural have also been used successfully in the preparation of the thiazole portion of thiamine (21) (see Scheme 6).

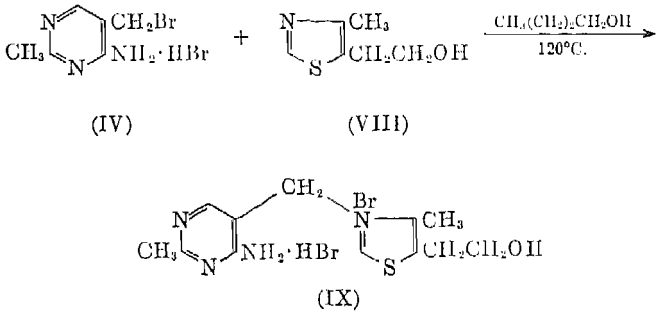
SCHEME 6



The Thiamine Molecule. Once either or both of the heterocyclic components have been prepared, there are three basically different approaches to the synthesis of thiamine itself.

Establishment of a linkage between the pyrimidine and thiazole moieties was the method used in the first synthesis of thiamine as reported by Williams and co-workers (41) (see Scheme 7). The thiazolium bromide hydrobromide (IX) formed is converted to thiamine hydrochloride (I) by the action of silver chloride in methanol.

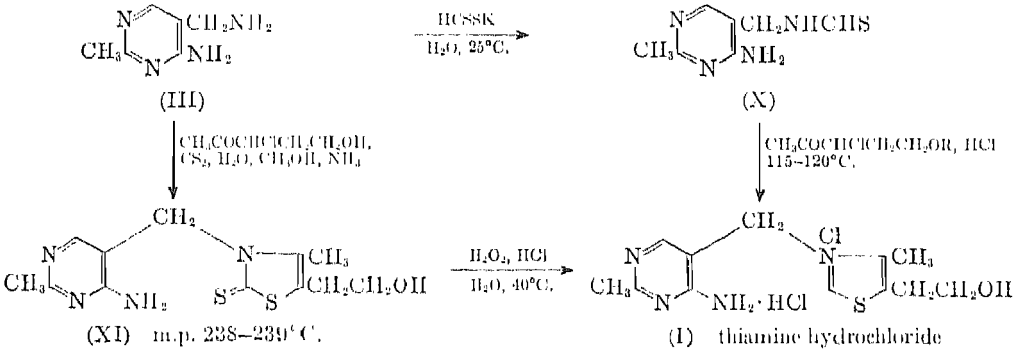
SCHEME 7



Construction of the thiazole ring on the preformed pyrimidine portion (VI in Scheme 4) was the general approach employed by Andersag and Westphal (1) and Todd and Bergel (4,29), who announced independent syntheses of thiamine hydrochloride at about the same time as did the Williams group. The two former groups of workers condensed 2-methyl-4-amino-5-(aminomethyl)pyrimidine (III) with potassium dithio-

formate and then condensed the product (X) with γ-acetyl-γ-chloropropanol (VII) (or an ester). See Scheme 8.

SCHEME 8

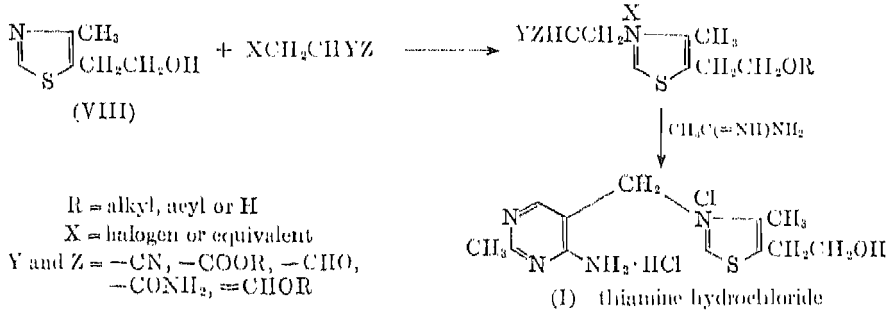


It has been reported (48) that improved yields of thiamine hydrochloride are obtained in the above sequence if a 2-alkoxy-2-methyl-3-chlorotetrahydrofuran is used in the condensation with (X). Also, the same general reaction sequence has been carried out (24) starting with 2-methyl-4-amino-5-(formamidomethyl)pyrimidine, 5-acetoxy-3-chloro-2-pentanone (the acetate of γ-acetyl-γ-chloropropanol (VII)), and hydrogen sulfide.

More recently, thiamine hydrochloride has been prepared (49) by the desulfurization of the corresponding 4-thiazoline-2-thione (2-thiothiazolone) (XI) (see Scheme 8).

Construction of the pyrimidine ring on the preformed thiazole ring has apparently intrigued few investigators as a possible synthesis of thiamine hydrochloride. A French patent (46) does propose, but not exemplify, the general scheme shown in Scheme 9.

SCHEME 9



Commercial Production. Industrial concerns manufacturing thiamine have not published the details of their methods, but it is known that in general the production syntheses follow the original equations of the Williams group in the U.S. (Schemes 3,7; and of Andersag and Westphal in Germany (Schemes 4,8).

Production and Prices. The production and sales data as given by the U.S. Tariff Commission are presented in Table II.

TABLE II. U.S. Thiamine Production and Price.

Year	Production, lb.	Sales		
		Lb.	Value, $	Unit value, $
1953	277,000	194,000	10,988,000	50.69
1952	224,000	145,000	9,574,000	66.21
1951	268,000	183,000	12,040,000	65.90
1950	237,400	178,600	12,005,100	67.22
1949	187,800	145,500	10,015,500	68.84

In considering these data it is well to remember that the quantity and value of sales fall significantly below production as the quantity sold excludes much of the thiamine diverted to foodstuffs. As a result of its more extensive use for the enrichment of cereal products in the decade 1941–1951, the price of thiamine salts was decreased by about 83%. Early in 1955, the price of thiamine hydrochloride and mononitrate was $100 per kilogram each. Thiamine hydrochloride U.S.P., and thiamine mononitrate are available in glass bottles and fiber drums.

Deficiency Symptoms and Uses

The maintenance requirements of thiamine for adults is in the range of 1.5 to 2.0 mg. per day, but the minimum requirement is raised substantially under certain circumstances, for example, pregnancy, hyperthyroidism, lactation, fever, diarrhea, diseases of the liver, and possibly alcoholism. Thiamine plays a role in carbohydrate metabolism, nerve function, and growth. Incomplete metabolism of carbohydrates, characteristic of thiamine deficiency, results in increased concentration of α-keto acids in the urine, which in turn leads to edema and deterioration of the nervous system, particularly the peripheral nerves of the extremities. The edema and serous effusions may occur with or without enlarged heart or congestive heart failure. Thiamine deficiency sufficient to cause cardiac damage is commonly designated *beriberi*.

Thiamine deficiency is remedied by parenteral or oral administration of thiamine. Although there is no strictly scientific basis for giving more than 10 to 20 mg. of thiamine daily, it is the general practice to give larger amounts, up to 100 mg. daily, in cases of severe deficiency. Essentially no risk is involved because of the very low toxicity of the vitamin.

Although thiamine plays an important role in the field of medicine, most of the

TABLE III. Requirements for Thiamine in Enriched Cereal Products.

Product	Requirement, mg./lb	
	Min.	Max.
Bread	1.1	1.8
Flour	2.0	2.5
Farina	1.66	—
Macaroni	4.0	5.0
Noodles	4.0	5.0
Corn meals	2.0	3.0
Corn grits	2.0	3.0
Milled white rice	1.7[a]	2.6[a]

[a] Interim Federal Specification N-R-00351, Dec. 10, 1953 (non-official).
Source: Refs. (10) and (11).

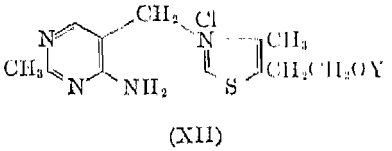
vitamin manufactured today is used in the enrichment of human foodstuffs, particularly cereals. The enrichment program, started in 1941, included the addition of iron, riboflavin (*q.v.*), niacin (*q.v.*) as well as thiamine (see Vol. **3**, p. 626). During this year about 8% of the thiamine ingested came from the enrichment of cereal products; by 1948 the contribution from enrichment had risen to about 25%. The levels of thiamine necessary for various foodstuffs to be labeled as "enriched" is in the range of 1.1 to 5.0 mg. per pound as defined by the Food and Drug Administration (see also Table III).

Derivatives

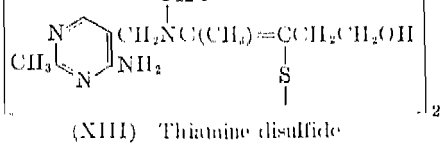
Cocarboxylase (diphosphothiamine), $C_{12}H_{19}ClN_4O_7P_2S.H_2O$ (XII, $Y=H_4P_2O_6$), formula weight of 478.87, is the pyrophosphoric ester of thiamine and the coenzyme of carboxylase. It crystallizes from methanolic hydrogen chloride as highly refractive stable crystals, m.p. 240–244°C. (decompn.). Cocarboxylase is soluble in water but essentially insoluble in organic solvents. The aqueous solutions are more prone to decomposition than are those of thiamine, and the solutions are highly acidic—pH 2.23 for a 0.3% solution at 25°C.

Cocarboxylase, together with protein (apoenzyme) and a metal activator constitute the *carboxylase enzyme system*. Purified yeast carboxylase is reported to contain seven gram atoms of magnesium and one mole of cocarboxylase for each 75 kg. of the proteinaceous apoenzyme (16). Manganese is as effective as magnesium as an activator, and reagents reactive with aldehydes, such as bisulfite, cyanides, and hydrazines, also exhibit a stimulatory effect, presumably because of reaction with the inhibitory end product, acetaldehyde. The function of the carboxylase involves the catabolism of pyruvic acid, $CH_3COCOOH$, a necessary intermediate of carbohydrate utilization in vertebrates. One mole of cocarboxylase has been reported to catalyze the decarboxylation of 840 moles of pyruvic acid within one minute at 30°C. (26).

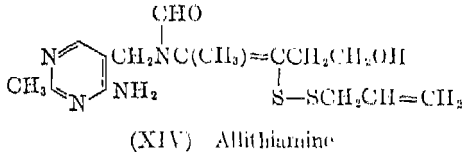
Cocarboxylase was first isolated from yeast (19,20) and a synthesis based upon the action of phosphorus oxychloride on thiamine hydrochloride was first realized by Stern and Hofer (28). The phosphorylation has been improved steadily and yields as high as 55% are now obtained (15,34,37,38,39). Synthetic cocarboxylase is in demand for biochemical research. In January 1954, the price was about $45.00 per gram.



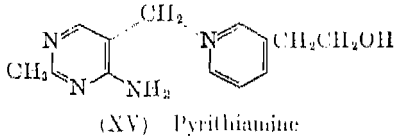
(XII)



(XIII) Thiamine disulfide



(XIV) Allithiamine



(XV) Pyrithiamine

Thiaminetriphosphoric acid (thiamine triphosphate, TTP), $C_{12}H_{20}ClN_4O_{10}P_3S.-\frac{1}{2}H_2O$ (XII, $Y=H_4P_3O_9$), formula weight 549.80, is another modification of thiamine of biological significance. It crystallizes from mixtures of water, alcohol, and acetone

as the hygroscopic hemihydrate, m.p. 228–232°C., which is freely soluble in water but insoluble in common organic solvents. This form of thiamine is synthesized by the phosphorylation of thiamine using much the same procedures as are employed for cocarboxylase (15,34,37,38,39). Thiamine triphosphate, which can function as a coenzyme for carboxylase, appears to be more stable than cocarboxylase, for example, the triphosphate is not hydrolyzed by adenosinetriphosphatase from muscle (35).

Analogs and Antimetabolites

Thiamine-like activity is not limited to thiamine itself but has been observed in several similar structures. Such activity is retained if (*a*) an ethyl group is substituted for methyl in the 2-pyrimidine position, (*b*) the 4-thiazolin-2-thione (XI) (23) is substituted for the thiazole portion of the thiamine molecule, or (*c*) the thiazole ring is opened to give "thiamine disulfide" (XIII) or allithiamine (XIV) (17). Vitamin activity with the disulfide and allithiamine is not surprising in view of the ease with which these compounds revert to thiamine in the presence of thiol compounds, for example, cysteine (25). Omission of the methyl group in the 2-pyrimidine or shifting position of this group to the 6-position results in products having roughly 10 per cent of the activity of thiamine. Several compounds with structures analogous to thiamine are known to be thiamine antimetabolites, that is, they counteract the vitamin activity of thiamine. Thus substitution of a pyridine ring for the thiazole ring in thiamine gives the so-called "pyrithiamine" (XV), a thiamine antagonist (45). Compounds in which the methyl group in the 2-pyrimidine position of thiamine is substituted by a benzyl or *n*-butyl group are also antagonistic to thiamine (9). Also, substitution of hydroxyl for amino in the 4-pyrimidine position results in antimetabolite activity.

Bibliography

(1) Andersag, H., and Westphal, K., *Ber.*, **70**, 2035 (1937).
(2) Association of Vitamin Chemists, *Methods of Vitamin Assay*, 2nd ed., Interscience, New York-London, 1951, pp. 107–27.
(3) Bechdel, S. I., Honeywell, H. E., Dutcher, R. A., and Knutsen, M. H., *J. Biol. Chem.*, **80**, 231 (1928).
(4) Bergel, F., and Todd, A. R., *J. Chem. Soc.*, **1938**, 26.
(5) Buchman, E. R., *J. Am. Chem. Soc.*, **58**, 1803 (1936).
(6) Clarke, H. T., and Gurin, S., *J. Am. Chem. Soc.*, **57**, 1876 (1935).
(7) Cline, J. K., Williams, R. R., and Finkelstein, J., *J. Am. Chem. Soc.*, **59**, 1052 (1937).
(8) Cline, J. K., Williams, R. R., Ruehle, A. E., and Waterman, R. E., *J. Am. Chem. Soc.*, **59**, 530 (1937).
(9) Emerson, G. A., and Southwick, P. L., *J. Biol. Chem.*, **160**, 169 (1945).
(10) *Federal Register*, **13**, No. 213, Oct. 30, 1948.
(11) *Federal Register*, **17**, No. 96, May 15, 1952.
(12) Grewe, R., *Z. physiol. Chem.*, **242**, 89 (1936).
(13) György, P., *Vitamin Methods*, Academic Press, N.Y., 1951.
(14) Hatcher, J. B., *J. Am. Chem. Soc.*, **69**, 465 (1947).
(15) Karrer, P., and Viscontini, M., *Helv. Chim. Acta*, **29**, 711 (1946).
(16) Kubowitz, F., and Luttgens, W., *Biochem. Z.*, **307**, 170 (1941).
(17) Lilly, V. G., Barnett, H. L., and Anderson, G. L., *Science*, **118**, 548 (1952).
(18) Lipmann, F., *Nature*, **138**, 1097 (1936).
(19) Lohmann, K., and Schuster, P., *Naturwissenschaften*, **25**, 26 (1937).
(20) Lohmann, K., and Schuster, P., *Biochem. Z.*, **294**, 188 (1937).
(21) Londergan, T. E., Hause, N. L., and Schmitz, W. R., *J. Am. Chem. Soc.*, **75**, 4456 (1953).
(22) McElroy, L. W., and Goss, H., *J. Biol. Chem.*, **130**, 437 (1939).

(23) Matsukawa, T., and Iwatsu, T., *J. Pharm. Soc. Japan*, **70**, 32 (1950); see also *C.A.*, **44**, 4477 (1950).
(24) Matsukawa, T., and Yurugi, S., *J. Pharm. Soc. Japan*, **69**, 508 (1949).
(25) Matsukawa, T., Yurugi, S., and Matsuoka, T., *Science*, **118**, 325 (1952).
(26) Peters, R. A., *Nature*, **146**, 387–391 (1940).
(27) Rosenberg, H. R., *Chemistry and Physiology of the Vitamins*, Interscience, New York-London, 1942, pp. 99–150.
(28) Stern, K. G., and Hofer, J. W., *Science*, **85**, 483 (1937).
(29) Todd, A. R., and Bergel, F., *J. Chem. Soc.*, **1937**, 364.
(30) Todd, A. R., Bergel, F., and Jacob, A., *J. Chem. Soc.*, **1936**, 1555.
(31) Todd, A. R., Bergel, F., Fraenkel-Conrat, H. L., and Jacob, A., *J. Chem. Soc.*, **1936**, 1601.
(32) U.S. Dept. Agr., *Handbook* No. 8, June 1950.
(33) U.S. Dept. Agr., *Misc. Publ.* No. **572**, 1945.
(34) Velluz, L., Amiard, G., and Bartos, J., *Bull. soc. chim. France*, **1948**, 871.
(35) Velluz, L., Amiard, G., and Bartos, J., *J. Biol. Chem.*, **180**, 1137 (1949).
(36) Wegner, M. I., Booth, A. N., Elvehjem, C. A., and Hart, E. B., *Proc. Soc. Exptl. Biol. Med.*, **45**, 769 (1940).
(37) Weijlard, J., *J. Am. Chem. Soc.*, **63**, 1160 (1941).
(38) Weijlard, J., and Tauber, H., *J. Am. Chem. Soc.*, **60**, 2263 (1938).
(39) Weil-Malherbe, H., *Biochem. J.*, **34**, 980 (1940).
(40) Williams, R. R., *J. Am. Chem. Soc.*, **58**, 1063 (1936).
(41) Williams, R. R., and Cline, J. K., *J. Am. Chem. Soc.*, **58**, 1504 (1936).
(42) Williams, R. R., and Spies, T. D., *Vitamin B_1*, Macmillan, N.Y., 1938.
(43) Williams, R. R., Waterman, R. E., Keresztesy, J. C., and Buchman, E. R., *J. Am. Chem. Soc.*, **57**, 536 (1935).
(44) Wintersteiner, O., Williams, R. R., and Ruehle, A. E., *J. Am. Chem. Soc.*, **57**, 517 (1935).
(45) Woolley, D. W., *Advances in Enzymol.*, **6**, 131 (1946).
(46) French Pat. 816,432 (May 3, 1937), I. G. Farbenindustrie.
(47) U.S. Pat. 2,179,984 (Nov. 14, 1940), H. Spiegelberg (to Hoffmann-LaRoche).
(48) U.S. Pat. 2,217,446 (Aug. 16, 1938), M. Klingenfuss (to Hoffmann-LaRoche).
(49) U.S. Pat. 2,592,930 (April 1952) T. Matsukawa and T. Iwatsu (to Takeda).

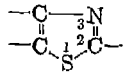
EARL PIERSON

THIAMYLAL, $C_{14}H_{24}N_2O_2S$. See *Stimulants and depressants of the nervous system*, Vol. **13**, p. 10.

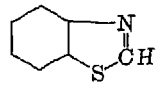
THIAZINES. See *Azine dyes*, Vol. **2**, p. 221; *Heterocyclic compounds*, Vol. **7**, p. 453; *Sulfur dyes*, Vol. **13**, p. 447.

THIAZOLE DYES

The thiazole dyes comprise a class of coloring matters characterized by the presence of the chromophoric thiazole grouping (I). Other dye classes that include some members having this grouping are anthraquinone dyes (*q.v.*), azo dyes (*q.v.*), cyanine dyes (*q.v.*), and sulfur dyes (*q.v.*). Some polymethine dyes (*q.v.*), including certain derivatives of rhodanine, S.CS.NH.CO.CH_2, also contain the thiazole grouping.



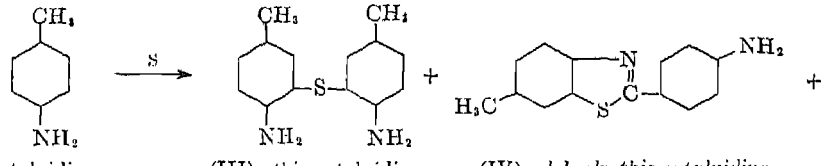
(I)



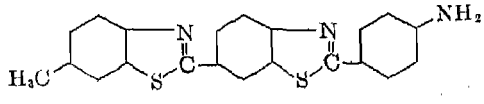
(II) Benzothiazole

The simplest derivatives of thiazole itself are not colored. A color occurs only when the thiazole ring is fused with one or more benzene nuclei, as in derivatives of *benzothiazole* (II), or is combined with a straight-chain conjugated system. Possibly the simplest thiazole dye known is obtained from *2-aminobenzothiazole*. When this compound is treated with hypochlorite (the essential product of this reaction is the azo compound), a bright red color immediately develops. One of the chief uses for 2-aminobenzothiazole or one of its C(4)- or C(6)-substituted derivatives is in the impregnation of paper to be used for legal documents and checks as an antiforgery measure. When an ink eradicator, such as hypochlorite solution, is applied to such paper a deeply colored blot develops (8).

The first dye containing a thiazole ring was Primuline, discovered in 1887 by Arthur Green, who obtained it by heating 2 moles of *p*-toluidine with 4 moles of sulfur at 200–280°C. and subsequently sulfonating the base with fuming sulfuric acid. However, it was later found that the reaction between sulfur and *p*-toluidine gives three products, which were identified as *thio-p-toluidine* (III), *dehydrothio-p-toluidine* (2-(*p*-aminophenyl)-6-methylbenzothiazole) (IV), and *bisdehydrothio-p-toluidine* (primuline base, 2-(*p*-aminophenyl)-6-(6-methyl-2-benzothiazolyl)benzothiazole) (V).



p-toluidine (III) thio-*p*-toluidine (IV) dehydrothio-*p*-toluidine



(V) bisdehydrothio-*p*-toluidine

The thiotoluidine does not come into consideration here since it does not contain the thiazole ring. The dehydrothiotoluidine or its sulfonic acid, although not a dye, is used as an intermediate. The sodium salt of the monosulfonic acid (primulinesulfonic acid) of primuline base is the dye *Primuline* (*C.I.* 812).

Homologs of *p*-toluidine, for example, *m*-4-xylidine (2,4-dimethylaniline) and

pseudocumidine (2,4,5-trimethylaniline), react with sulfur to form dehydrothio-*m*-xylidine and dehydrothiopseudocumidine, respectively.

All of these compounds can be diazotized and coupled with phenolic or amino derivatives to form azo dyes substantive to cotton, or can be alkylated to produce mordant or direct dyes. Other valuable thiazole intermediates for azo dyes may be obtained from thionated derivatives of 6-amino-1-naphthol-3-sulfonic acid (J acid) and from acylacetamidobenzothiazole derivatives. Several anthraquinone vat dyes contain a thiazole ring.

A few thiazole dyes find use as biological stains (see also *Stains, microscopical (biological)*).

Primuline Group

MANUFACTURE OF DEHYDROTHIOTOLUIDINESULFONIC ACID AND PRIMULINE

Fusion. Into a steel, oil-jacketed, melt kettle fitted with reflux condenser, 334 lb. *p*-toluidine, 220 lb. sulfur, and 1.5 lb. sodium carbonate are charged. The contents are heated until melted, the agitator is started, and the temperature is slowly raised to 185°C. and maintained at 185–188°C. for 13 hr. At the end of this period, the temperature of the melt is raised to 245°C. over 5 hr. and held at this temperature for about 1 hr. The melt is blown into a vented pan where it is allowed to cool overnight. Weight: about 375 lb. of primuline melt. It is ground with 3 lb. sodium carbonate to prevent lumping when introduced into sulfuric acid.

Sulfonation. Eleven hundred pounds of sulfuric acid (monohydrate), is charged into a steam- and brine-jacketed sulfonator, and 385 lb. of ground primuline melt is screened in over approximately 4 hr. The temperature rises to 80–85°C., and is held at this point until all is in solution. The solution is cooled with brine to 35°C. and then 510 lb. 65% oleum is slowly added so the temperature does not rise above 40°C. It is held at 40°C. until a test is soluble in dilute ammonia and then cooled to 35°C. and blown into ice and water. It is then filtered and washed acid-free to Congo Red test paper.

Separation. The washed filter cake is added to 1500 lb. water, heated to 60°C., and treated with about 30 lb. 100% ammonia to give a clear solution. It is cooled and allowed to stand for 3–4 days. The precipitated ammonium salt of dehydrothiotoluidinesulfonic acid is filtered and washed with weak ammonia water. The filter cake is then dried. Yield: about 110 lb. of the dry ammonium salt.

Sometimes it is desired to have the free dehydrothio-*p*-toluidine base. In that case the finished melt may be distilled in a cast-iron still under vacuum (10–15 mm.) at 150–300°C. in the vapor, or 200–390°C. in the molten mass. Another method (6) is to extract the melt with alcohol, which dissolves the thiotoluidine and dehydrothiotoluidine and leaves the primuline base. The alcoholic extract is evaporated to dryness and the toluidine and part of the thiotoluidine are driven off by heating to 250°C. The dehydrothiotoluidine is sulfonated by dissolving in sulfuric acid (monohydrate) and adding 25% oleum. Dehydrothiotoluidinesulfonic acid may be further sulfonated to the disulfonic acid by baking procedures (3,9).

To obtain Primuline, about 132 lb. sodium carbonate is added to the filtrate obtained from the separation of the dehydrothiotoluidinesulfonic acid and boiled for 5–6 hr. to remove the ammonia. It is cooled to 70°C. and salt is added to precipitate

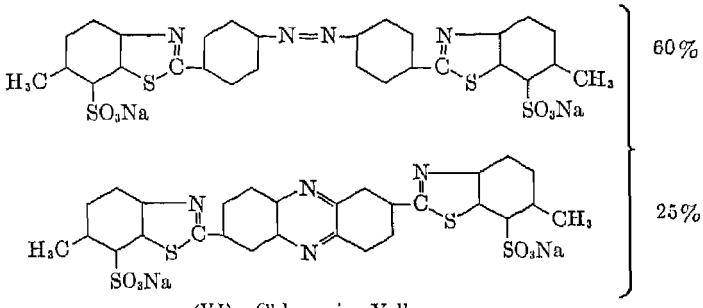
the sodium salt of bisdehydrothiotoluidinesulfonic acid (Primuline) which is then cooled, filtered, and dried. Yield: approximately 330 lb. of concentrated Primuline.

If the melt was first extracted with alcohol, the primuline base residue is sulfonated with 25% oleum.

In 1953 the U.S. production of Primuline was 277,000 lb. and the sales 247,000 lb. at a unit value of $0.98/lb.

PROPERTIES AND RELATED DYES

Dehydrothio-*p*-toluidinesulfonic acid has no affinity for the cotton fiber. Oxidation of its sodium salt with sodium hypochlorite yields **Chloramine Yellow** (Direct Fast Yellow) (*C.I.* 814), which according to Schubert (15) has the constitution (VI).

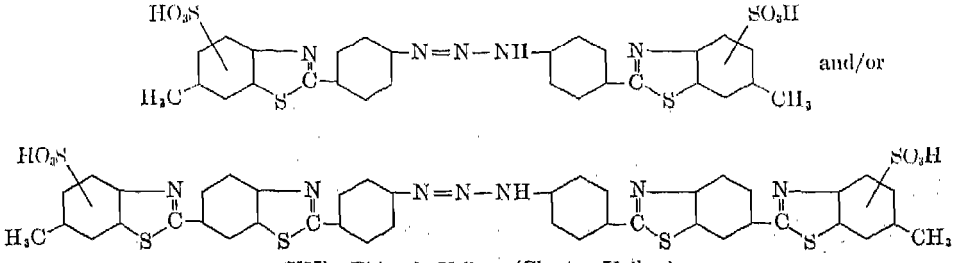


(VI) Chloramine Yellow

Chloramine Yellow dyes cotton directly in a yellow shade having superior fastness to chlorine and light and is not discharged by reducing agents. It is one of the best direct yellows known. In 1953 the U.S. production was 417,000 lb. and the sales were 400,000 lb. at a unit value of $1.43/lb.

Primulinesulfonic acid or its sodium salt, Primuline (*C.I.* 812), will combine directly with the cotton fiber, where it can be diazotized and coupled with phenolic or amino compounds. The dye is also used as a biological stain.

Both dehydrothiotoluidinesulfonic acid and primulinesulfonic acid can be diazotized and coupled with another mole of the undiazotized sulfonic acid to form diazoamino compounds which dye cotton directly in strong bright yellow shades having poor fastness qualities, for example, **Thiazol Yellow** (Clayton Yellow) (*C.I.* 813) (VII).



(VII) Thiazol Yellow (Clayton Yellow)

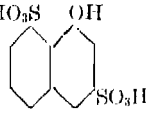
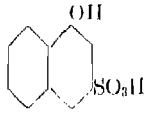
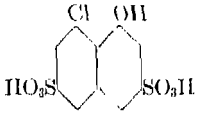
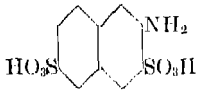
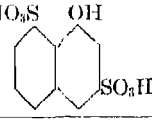
Thiazol Yellow paper is used as an indicator for free caustic alkali and the dye itself as a biological stain.

Azo Dyes from Dehydrothio-*p*-toluidine (IV) and -*m*-xylidine Bases. The red and rose shade dyes, obtained by coupling the diazo compounds of dehydrothio-*p*-

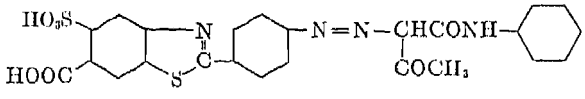
46483

toluidine (DT) and dehydrothio-*m*-xylidine (DX) with naphthol- and naphthylamine-sulfonic acids, are the most important. See Table I.

TABLE I. Azo Dyes from Dehydrothio-*p*-toluidine and -*m*-xylidine Bases.

Diazo compd.	Coupler	Dye	C.I. No.	Remarks
DT		Erika 2GN Pontamine Fast Pink GGN	126	Bluish pink on cotton, red on wool
DT		Geranine G	127	Yellowish pink to bluish pink
DT		Diamine Rose BD Erie Pink 2B Calcomine Pink RX Conc. Direct Pink BTA Pheno Pink RX Conc.	128	Pink on cotton
DX		Salmon Red	129	Salmon red on cotton
DX		Erika B Pontamine Fast Pink EB Ex. Erica B	130	Pink on cotton and wool

Azo Dyes from Dehydrothio-*p*-toluidinesulfonic Acid (DTS). Treatment of *N*-acetyldehydrothio-*p*-toluidinesulfonic acid (2-(*p*-acetamidophenyl)-6-methyl-5-benzothiazolesulfonic acid) with potassium permanganate in neutral solution converts it into 2-(*p*-acetamidophenyl)-5-sulfo-6-benzothiazolecarboxylic acid (18), which after hydrolysis is diazotized and coupled with acetoacetanilide to give **Benzo Pure Yellow FF** (VIII) (14, p. 2292; 17); this is readily soluble in water and dyes cotton in a clear greenish-yellow shade.



(VIII) Benzo Pure Yellow FF

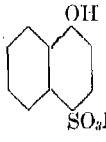
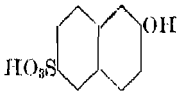
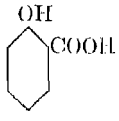
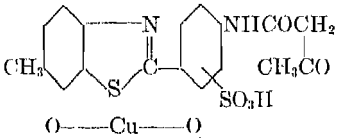
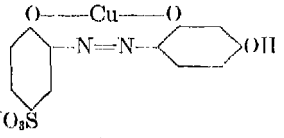
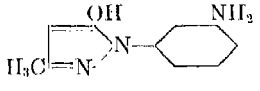
Oxidation of 2-(*p*-aminophenyl)-5-sulfo-6-benzothiazolecarboxylic acid with sodium hypochlorite gives a greenish-yellow dye of excellent lightfastness (23).

Some of the dyes from the diazo compound of DTS with various couplers are shown in Table II.

Azo Dyes from Dehydrothio-*p*-toluidinedisulfonic Acid. Dehydrothiotoluidinedisulfonic acid is the basis for a number of interesting direct dyes. For example, it is diazotized and coupled to *o*-acetoacetanisidide to give **Sirius Supra Yellow 5G** (Pr. 99) (13, p. 1664; 19), also sold as Solantine Yellow 8GL and Fastusol Yellow L5GA, which has good solubility in water and dyes cotton directly in a greenish-yellow shade of good lightfastness. When the disulfonic acid is coupled to the mixed urea derivative of J acid and *p*-aminoacetanilide, **Sirius Scarlet B** is obtained (13, p. 1290).

Yellow to orange-red to brown shades on cotton of excellent fastness to light and washing and having good discharge properties are obtained with symmetrical diazo dyes produced from dehydrothiotoluidinedisulfonic acid. The diazo of dehydrothiotoluidinedisulfonic acid is coupled to aniline, *o*-anisidine or cresidine (5-methyl-*o*-anisidine) and the resulting aminoazo compound is phosgenated (30).

TABLE II. Azo Dyes from Dehydrothio-*p*-toluidine Monosulfonic Acid.

Coupler	Dye	*C.I.* No.	Remarks
	Rosophenine 10B Calcomine Brill. Pink SX Dbl. Conc. Paranol Fast Red SG Pontamine Pink 2B Conc. 200%	225	Pink to red on cotton, red on wool
	Thiazine Red GN	226	Pink on cotton, scarlet-red on wool
	Oriol Yellow Cotton Yellow R	223	Yellow on cotton, after-treated with Cu salts gives slightly redder tint
	Dianil Yellow 5 GA Diphenyl Pure Yellow 5G	Pr. 249	(1)
	Dianil Yellow 3 GW	—	Light- and washfast (27)
	Igenal Brown CM	—	Coupler made from 4-chlorometanilic acid (6-chloroaniline-3-sulfonic acid) and resorcinol (14, p. 2164)
	Zambesi Orange R	—	Dyed on cotton, diazotized *in situ* and developed with 2-naphthol (12)

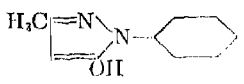
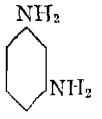
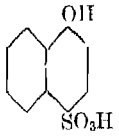
Azo Dyes from Primulinesulfonic Acid. Beside the dye produced on the fiber (see p. 51), other primuline dyes are produced in substance. See Table III.

Other similar dyes are *C.I.* 221, 222, 228, 231, 233, 646, 648, 650.

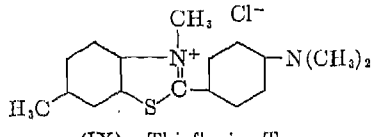
Mixtures of DTS and primulinesulfonic acid may also be used as diazo components to obtain dyes similar to those given above under their separate headings. The two sulfonic acids are normally used as the mixture obtained directly from the melt, or the separated acids can be mixed again in any proportion to give the shade desired. Whereas dehydrothiotoluidine colors on the fiber are bleached white when treated with sodium hydrosulfite, $Na_2S_2O_4$, Primuline colors leave the fiber yellow.

Thioflavine Dyes. These are produced by alkylation of dehydrothiotoluidine, dehydrothiotoluidinesulfonic acid, or primuline base or -sulfonic acid.

TABLE III. Azo Dyes from Primulinesulfonic Acid.

Coupler	Dye	*C.I.* No.	Remarks
	Dianil Yellow R	649	Golden-yellow on cotton
$CH_3COCH_2COOC_2H_5$	Dianil Yellow 3G	647	Yellow on cotton
	Alkali Brown	220	Reddish brown on cotton
	Rosophenine 5G	227	Pink to red on cotton

Thioflavine T (*C.I.* 815)(IX) is produced by methylating dehydrothiotoluidine with methanol and hydrochloric acid in an enameled autoclave at 170–175°C. for 6–7 hr. (pressure 35–45 atm.). The free amino group is dimethylated and the nitrogen in the thiazole is quaternized with the methyl chloride, forming the trimethyl derivative, which is the dye. The autoclave charge is diluted with water, neutralized with sodium hydroxide, and filtered. Of the total dehydrothiotoluidine charge, twenty-five per cent is only dimethylated and, as it is insoluble, is separated in this filtration. The filtrate is salted with sodium sulfate to obtain the desired trimethyl derivative. The dimethyl derivative collected from several operations is remethylated (10, p. 1184). Thioflavine T dyes mordanted cotton to a pure greenish yellow. It is also used in making organic pigments (see Vol. **10**, p. 675).



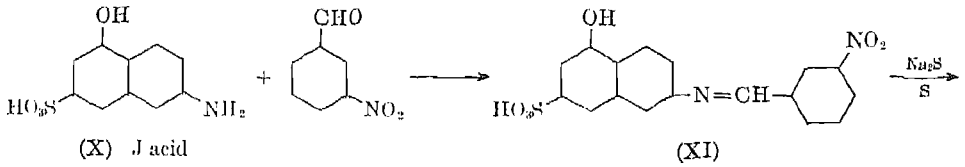
(IX) Thioflavine T

Zitroflavine 8G is the zinc salt of triethyl thioflavine.

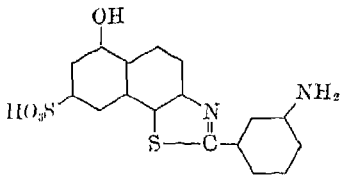
Thioflavine S (*C.I.* 816) is the sulfonic acid of dialkylated primuline base. It is made by dissolving the dialkylprimuline base in sulfuric acid (monohydrate) at not over 40°C. The solution is sulfonated by feeding in 65% oleum, followed by heating to 90°C., and holding that temperature for 3 hr. The sulfonation reaction mass is drowned, filtered, and washed with water. Thioflavine S dyes cotton directly to a canary yellow (14, p. 2509). Both Thioflavine T and S are used as biological stains.

Thiazole Dyes from J Acid

Thionation of *N*-benzyl or -benzylidene derivatives (such as (XI)) of J acid (X) with sulfur and alkali sulfide yields thiazole derivatives (such as the 2-(*m*-aminophenyl)-thiazole derivative, XII) (16). This thiazole may be coupled with diazobenzene derivatives (13, pp. 1577–78, 1580, 1626) to form aminoazo compounds, for example, Diazo Brilliant Scarlet G (XIII), which may be further diazotized on the fiber and

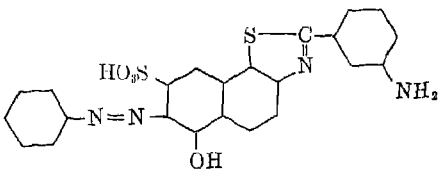


(X) J acid (XI)



(XII)

developed with 2-naphthols. These dyes give vivid shades which have good fastness to acids and alkalies but are only moderately fast to light (5).



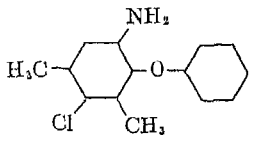
(XIII)

Different shades are obtained if the *p*-aminophenyl isomer is substituted for the *m*-amino derivative (XII).

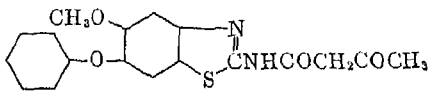
Azoic Thiazole Dyes from Couplers Made from Acylacetamidobenzothiazole Derivatives

As an example, the printing mixture *Rapidogen Golden Yellow IGL* is prepared from the diazo compound of 5-chloro-*o*-toluidine (stabilized with *N*-methylglycine (sarcosine)) and the coupler 2-acetoacetamido-5-methoxy-6-ethoxybenzothiazole (*N*-(6-ethoxy-5-methoxy-2-benzothiazolyl)acetoacetamide) (4,21).

Yellow dyes to be used either as developed dyes or lakes can be obtained, for example, from the diazo compound from 2-amino-4,6-dimethyl-5-chlorophenyl phenyl ether (XIV) (stabilized with sarcosine) and 2-acetoacetamido-5-methoxy-6-phenoxybenzothiazole (XV) (29).



(XIV)

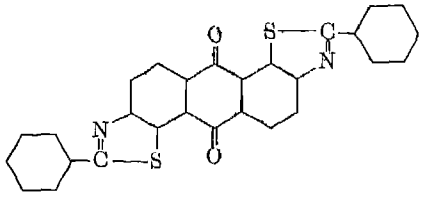


(XV)

Thiazole Dyes of the Vat Series

There are on the market several anthraquinone dyes (*q.v.*) containing a thiazole ring. The oldest and best known is Algol Yellow GC (Pr. 9) (XVI), also sold as Cibanone Yellow GC Paste or Ponsol Flavone GC Double Paste. It can be made by

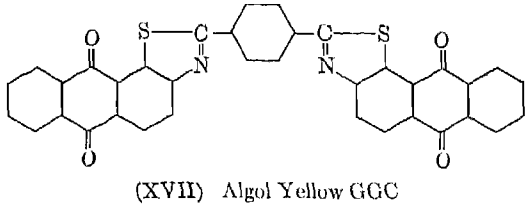
reaction of 2,6-diaminoanthraquinone with benzotrichloride (α,α,α-trichlorotoluene) and sulfur in molten naphthalene. The reactants are heated in an agitated enameled autoclave for 21 hr. and held at 218–220°C. for the last 9 hr. The melt is blown by means of nitrogen into an agitated pressure apparatus (diluting kettle), cooled to about 90°C., diluted with chlorobenzene, and after 2 hr. blown at 120°C. into an agitated filter box. The dye is obtained in the form of yellow crystals which dissolve in



(XVI) Algol Yellow GC

concentrated sulfuric acid and in 1,2,4-trichlorobenzene with a yellow color. It dyes cotton yellow from a violet vat (7; 10, pp. 2002–13; 22; 25; 28; 31; 32). In 1953 the U.S. production was 2,269,000 lb. and the sales 2,030,000 lb. at a unit value of \$1.49/lb.

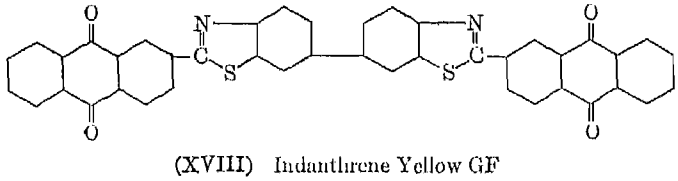
A slightly more lightfast dye than Algol Yellow GC is **Algol Yellow GGC** (XVII), obtained from 1 mole of terephthaloyl chloride, p-$C_6H_4(COCl)_2$, 2 moles of 2-amino anthraquinone, and sulfur (11).



(XVII) Algol Yellow GGC

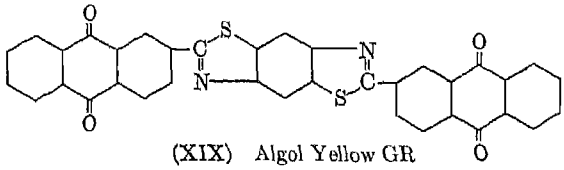
A series of fast orange dyes similar to Algol Yellow GGC from 2,5-dialkoxyterephthalic acids as intermediates has been patented (33).

Indanthrene Yellow GF (Pr. 451) (XVIII) (10, pp. 2144–52), known also as Carbanthrene Yellow GF Paste, is made by fusing together 2-methylanthraquinone,



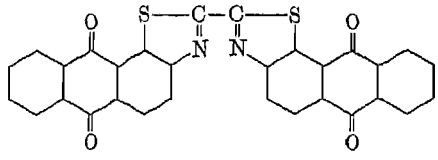
(XVIII) Indanthrene Yellow GF

benzidine, and sulfur, extracting with sodium sulfide, and oxidizing with sodium hypochlorite. If p-phenylenediamine is used instead of benzidine, **Algol Yellow GR** (XIX) is obtained (2).

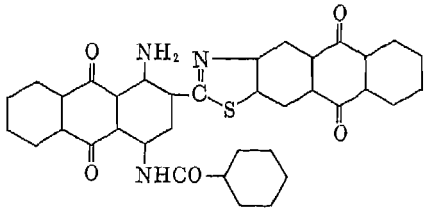


(XIX) Algol Yellow GR

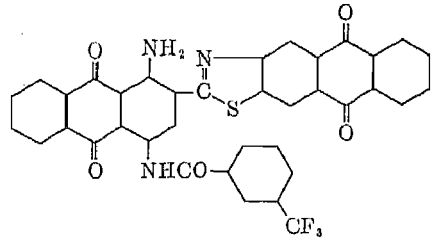
By heating together 2 moles of 1-mercapto-2-aminoanthraquinone and 1 mole of glyoxal sulfate (see Vol. **13,** pp. 506, 511) in sulfuric acid (96%), **Algol Yellow 8G** (XX) is formed (20). It dissolves in sulfuric acid with a brown-yellow color and gives a violet vat. However, it is used only as a shading color.



(XX) Algol Yellow 8G



(XXI) Indanthrene Blue CLG



(XXII) Indanthrene Blue CLB

Indanthrene Blue CLG (Vat Blue CLG; see also *Vat dyes*) (XXI) is obtained in blue-violet needles which give a green solution in concentrated sulfuric acid (24). It dyes cotton from a violet vat a greenish-blue shade of outstanding light- and chlorine-fastness.

Indanthrene Blue CLB (XXII) forms blue-red needles having a metallic luster which give an olive-green solution in concentrated sulfuric acid (26). It dyes cotton from a violet vat a clear intense greenish-blue shade having excellent fastness properties.

Bibliography

(1) *BIOS Final Rept.*, No. **961,** 112 (1945).
(2) *BIOS Final Rept.*, No. **1493,** 3 (1946).
(3) *FIAT Final Rept.*, No. **1016,** 17 (1947).
(4) Dahlen, M. A., *Office of Tech. Services Rept.*, **PB 2461,** Appendix No. 23 (1946).
(5) Fierz-David, H. E., *Technologie der Textilfasern*, Vol. III (*Künstliche Organische Farbstoffe*), Springer, Berlin, 1926, p. 86.
(6) Fierz-David, H. E., and Blangey, L., *Fundamental Processes of Dye Chemistry*, 5th ed., Interscience, New York-London, 1949, p. 334.
(7) Friedländer, Vol. XI, pp. 635–637.
(8) Kirk, W., Jr., Johnson, J. R., and Blomquist, A. T., *J. Org. Chem.*, **8,** 557 (1943).
(9) *Office of Tech. Services Rept.*, **PB 25624,** 1136 (1932).
(10) *Office of Tech. Services Rept.*, **PB 25626** (1930–1939).
(11) *Office of Tech. Services Rept.*, **PB 73726,** 267 (1941).
(12) *Office of Tech. Services Rept.*, **PB 74024,** 379 (1946).
(13) *Office of Tech. Services Rept.*, **PB 74025** (1946).
(14) *Office of Tech. Services Rept.*, **PB 74026** (1946).
(15) Schubert, M., *Ann.*, **558,** 10 (1947).
(16) Ger. Pat. 165,126 (Sept. 25, 1905), Farbenfabriken Bayer; Friedländer, Vol. VIII, 186.
(17) Ger. Pat. 274,490 (May 4, 1914), Farbenfabriken Bayer; Friedländer, Vol. XII, p. 336.
(18) Ger. Pat. 277,395 (July 13, 1914), Farbenfabriken Bayer; Friedländer, Vol. XII, p. 142.
(19) Ger. Pat. 293,333 (June 26, 1916), Farbenfabriken Bayer; Friedländer, Vol. XII, p. 337.

(20) Ger. Pat. 421,236 (Oct. 22, 1925), Badische Anilin & Soda Fabrik, Friedländer, Vol. XV, p. 689.
(21) U.S. Pat. 2,030,327 (Feb. 11, 1936), G. Schrader and W. Zerweck (to General Aniline Works).
(22) U.S. Pat. 2,097,867 (Nov. 2, 1937), A. J. Wuertz and W. L. Rintelman (to Du Pont).
(23) U.S. Pat. 2,098,599 (Nov. 9, 1937), M. Schubert (to General Aniline Works).
(24) U.S. Pat. 2,147,569 (Feb. 14, 1939), E. Berthold and J. Mueller (to General Aniline Works).
(25) U.S. Pat. 2,150,092 (March 7, 1932), E. E. Beard (to Du Pont).
(26) U.S. Pat. 2,244,655 (June 3, 1941), H. Schlichenmaier, L. W. Berlin, and E. Berthold (to General Aniline & Film Corp.).
(27) U.S. Pat. 2,283,823 (May 19, 1942), A. Sieglitz and M. Reuter (to General Aniline & Film Corp.).
(28) U.S. Pat. 2,289,292 (July 7, 1942), W. P. Munro and G. M. Smyth (to American Cyanamid Co.).
(29) U.S. Pat. 2,306,681 (Dec. 29, 1942), W. Zerweck, J. Riedmair, and W. Brunner (to General Aniline & Film Corp.).
(30) U.S. Pat. 2,384,283 (Sept. 4, 1945), K. F. Conrad and L. F. Koberlein (to Allied Chemical & Dye Corp.).
(31) U.S. Pat. 2,453,410 (Nov. 9, 1948), J. F. Cullinan and L. D. Lytle (to American Cyanamid Co.).
(32) U.S. Pat. 2,473,872 (June 21, 1949), M. H. Fleysher (to Allied Chemical & Dye Corp.).
(33) U.S. Pat. 2,652,400 (Sept. 15, 1953), N. W. Solonen and D. I. Randall (to General Aniline & Film Corp.).

STUART D. KERR AND MARTHA T. RATHGEB

THIAZOLES. See *Heterocyclic compounds*, Vol. **7**, p. 441; *Thiazole dyes*.

THICKENERS. See *Sedimentation*.

THIMEROSAL, $C_6H_4(SHgC_2H_5)COONa$. See *Mercury preparations*, Vol. 8, p. 895.

THINNERS. See *Coatings, industrial*; *Paint*.

THIOACETALS, $RCH(SR')_2$. See *Mercaptals*.

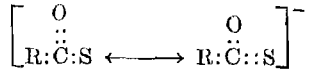
THIO ACIDS

A thio acid may be considered to be derived from the corresponding oxygen acid by replacement of some or all of the oxygen atoms with bivalent sulfur atoms.

Inorganic thio acids, sometimes referred to as "sulfo acids," are of interest mainly in the form of their salts or esters (for examples, see *Phosphorus compounds, inorganic*, Vol. **10**, pp. 493, 507; *Thiosulfuric acid*). Thio acid derivatives are formed by the more negative elements that have acidic sulfides. Among these elements are gold, mercury, and boron; the group IV elements carbon, silicon, germanium, and tin; the group V elements phosphorus, vanadium, arsenic, antimony, and bismuth; and the group VI elements sulfur (see "Thiosulfonates" under *Sulfur compounds, organic*), chromium, molybdenum, and tungsten. The methods of formation of inorganic thio acid salts include treatment of a solution of the requisite acidic sulfide with a basic sulfide such as sodium sulfide, fusion of the components, or passage of hydrogen sulfide through a solution of the oxysalt (11).

Organic thio acids have been reviewed by Connor (6), and many of their reactions have been summarized by Tarbell and Harnish (18).

Structure. Acids such as monothio acids containing both oxygen and sulfur seem to exist in only one form; this is not surprising in view of the equivalence of the oxygen atoms (attributable to resonance) in inorganic and organic oxygen acids. Thus for monothio carboxylic acids, both the *thiol* (—SH) and *thiono* (>C=S) forms are assumed to contribute to the resonance hybrid of the anion:



although recent spectroscopic evidence indicates that thioacetic acid, at least, is substantially completely in the thiol form (9). As would be expected, replacement of the mobile hydrogen atom(s) or the hydroxyl group(s) by a covalently bonded group results in an unequivocal structure, which is of either the thiol or thiono type; for example, esters of both the thiol (RCOSR′) and the thiono (RCSOR′) types are known.

Nomenclature. For the acids themselves, including those containing oxygen as well as sulfur, a general (thio) name with no structural implications is preferable to a thiol or thiono name; for example, monothio- or dithiophosphoric acid, thioacetic acid. However, for distinguishing two or more possible isomeric structures (usually isolated only in the case of derivatives), specific thiol or thiono names may be used, as ethyl thiolacetate and ethyl thionoacetate; alternatively the attachment of the substituting group may be indicated by *O*- or *S*-, as *O,O*-diethyl *O*-*p*-nitrophenyl thiophosphate, $(C_2H_5O)_2PS(OC_6H_4NO_2)$; *O*-ethyl *S*-methyl hydrogen dithiophosphate, $(C_2H_5O)(CH_3S)POSH$ (see Vol. **10**, pp. 496, 507).

The three types of specific names shown below for the three possible thioacetic acids (or their derivatives) are analogous to those used for carboxylic acids (see Vol. **1**, p. 140); the general names corresponding to thioacetic acid but formed with suffixes are ethanethioic and methanecarbothioic.

CH_3COSH	CH_3CSOH	CH_3CSSH
thiolacetic acid	thionoacetic acid	dithioacetic acid
ethanethiolic acid	ethanethionic[a] acid	ethanethionothiolic acid
methanecarbothiolic acid	methanecarbothionic acid	methanecarbodithioic acid

[a] "Thionic" acid in this sense should not be confused with the term thionic acid (*q.v.*) as applied to acids of the general formula $H_2S_nO_6$.

"Thioglycolic acid" (*q.v.*) is a misnomer for mercaptoacetic acid, $HSCH_2COOH$, and "thiosalicylic acid" for *o*-mercaptobenzoic acid, HSC_6H_4COOH, used for making thioindigoid dyes (see Vol. **7**, p. 823) and therapeutically in the form of its heavy-metal derivatives such as thimerosal, N.F. IX (Merthiolate) (see *Mercury preparations*).

Organic Monothio Acids

PHYSICAL AND CHEMICAL PROPERTIES

The lower aliphatic thio acids are liquids or low-melting solids. In general their alkali salts are soluble in water and the heavy-metal salts are insoluble, decomposing to metallic sulfides when heated with water, although lead thioacetate may be recrystallized from water. Higher aliphatic thio acids are not known, but many esters have been prepared.

Thioformic acid, HCOSH, is an unstable liquid which quickly decomposes to an amorphous product. *Thioacetic acid,* CH_3COSH, however, can be distilled with little loss at its b.p. of 87.5°C.; d_4^{20}, 1.0696; n_D^{20}, 1.4636; m.p., −75°; the boiling point, lower than that of acetic acid, indicates less association than is shown by acetic acid. Thioacetic acid has an odor resembling that of acetic acid and hydrogen sulfide. It is soluble in water and easily so in organic solvents. *Thiopropionic acid,* CH_3CH_2COSH, is an unpleasantly pungent liquid, b.p. 108.3–109.5°C., which also can be dis-

tilled. *Thiobenzoic acid*, C_6H_5COSH, pale yellow, b_{10} 85–87°C.; n_D^{20}, 1.6030. The lower homologs of the $(COSH)_2$ series (corresponding to dicarboxylic acids) that are stable melt at or below room temperature, indicating the weakness of the intermolecular forces. The resonance energy of the —COSH group is reportedly much smaller than that of the —COOH group.

Thio acids acylate amines much more readily than do carboxylic acids (13) and much milder conditions are possible (8,15,16); moreover, they sometimes function well where carboxylic acids fail:

$$RCOSH + R'NH_2 \longrightarrow RCONHR' + H_2S$$

Thio acids usually react with alcohols to form oxygen esters, but thiol esters are also formed to some extent:

$$H_2O + RCOSR' \longleftarrow RCOSH + R'OH \longrightarrow RCOOR' + H_2S$$

Addition of thio acids to unsaturated compounds, frequently with a peroxide as a catalyst, results in "abnormal" addition in the sense of Markovnikov's rule and yields thiol esters, which upon hydrolysis afford mercaptans (*q.v.*; see also ref. 2):

$$RCOSH + CH_2{=}CHR' \longrightarrow RCOSCH_2CH_2R' \xrightarrow{H_2O} RCOOH + HSCH_2CH_2R'$$

Salts of thio acids are oxidized by iodine or similar agents to diacyl disulfides:

$$2\,RCOSNa + I_2 \longrightarrow RCOSSCOR + 2\,NaI$$

Thioacetic acid has been said to react explosively with strong nitric acid.

Thioacetic acid has been recommended as a convenient substitute for hydrogen sulfide in analytical operations, and also has certain other analytical uses.

PREPARATION

Most preparations of monothio acids involve treatment of an acid chloride or anhydride with a metal hydrosulfide, or with hydrogen sulfide and acidic or basic catalysts. Thus, thiobenzoic acid forms in 61–76% yield upon reaction of benzoyl chloride with potassium hydrosulfide (19), and thioacetic acid in 72–76% yield upon reaction of hydrogen sulfide with acetic anhydride and a little sodium hydroxide (10) or in somewhat greater yield in the presence of 1% of pyridine in the cold (17):

$$C_6H_5COCl + 2\,KSH \longrightarrow C_6H_5COSK + KCl + H_2S$$

$$C_6H_5COSK + HCl \longrightarrow C_6H_5COSH + KCl$$

$$(CH_3CO)_2O + H_2S \xrightarrow{OH^-} CH_3COSH + CH_3COOH$$

Conversion of a dithio acid to its thiono chloride, followed by hydrolysis, yields a monothio acid, as do recent promising methods which result in RCOSH upon treatment of the mixed anhydride, $RCOOCOOC_2H_5$, with hydrogen sulfide (8,16).

Monothio acids are also obtainable from the reaction of a diaroyl sulfide, a diaroyl disulfide, or a phenyl ester with potassium hydrosulfide, as well as from the reactions of a Grignard reagent with carbon oxysulfide and of a carboxylic acid with phosphorus pentasulfide (10,19).

DERIVATIVES

Esters (see also *Mercaptans*). *Thiol esters* (*S*-esters), RCOSR', are hydrolyzed to RCOOH and R'SH much more rapidly in alkaline than in acidic solution. The

relative rates of hydrolysis of carboxylic and thiol esters under alkaline conditions depend upon the structure of the ester, but the acidic hydrolysis of carboxylic esters occurs more rapidly.

Aminolysis of thiol esters to an *N*-substituted carboxamide and a mercaptan proceeds more rapidly than alcoholysis or hydrolysis:

$$RCOSR' + H_2NR'' \longrightarrow RCONHR'' + HSR'$$

The fact that amides can be formed in good yield under essentially physiological conditions has resulted in considerable interest in such reactions as models for biological acylations (15), such as those involving coenzyme A (see *Pantothenic acid*).

Desulfurization of a thiol ester with Raney nickel provides a useful and apparently rather general synthesis of an alcohol if the nickel is fresh, or of an aldehyde if the nickel has been deactivated (ref. 14, p. 204):

$$RCHO \longleftarrow RCOSR' \longrightarrow RCH_2OH$$

Heating the thiol ester with nickel that has first been heated to desorb hydrogen yields products such as RSR, RSR', and R'SR'. Lithium hydride also reduces thiol esters to aldehydes.

Ordinary nuclear substitution of esters of thiophenol by electrophilic reactions occurs only in exceptional instances. Fries rearrangements are also unsuccessful, the products being trithio orthoesters.

The usual preparation of thiol esters is by reaction of a mercaptan with an acid chloride, frequently (but not necessarily) in the presence of pyridine. Anhydrides are occasionally used instead of an acid chloride. The esters may also be obtained by reaction of an acid chloride with a metal mercaptide, which may result in somewhat lower yields, but easier purification; of a thio acid and an unsaturated compound or an epoxide; of a thio acid salt and an alkyl halide or *p*-toluenesulfonate; or by hydrolysis of a thioimido ester (obtained as on p. 62, or from a nitrile with a mercaptan and hydrogen chloride).

The thiol ester is much less favored in the equilibrium between carboxylic acids and mercaptans than is the carboxylic ester in the analogous reaction of an alcohol. Homocysteine, $CH_2(SH)CH_2CH(NH_2)COOH$, in the presence of acid nevertheless undergoes cyclization to the thio lactone.

Certain thiol esters are useful local anesthetics. Antispasmodic activity has also been reported for thiol esters.

Thiono esters (*O*-esters), RCSOR', are easily hydrolyzed to hydrogen sulfide and the corresponding oxygen ester. Owing also to their ease of oxidation, they are much less stable than the isomeric thiol esters. Thiono esters may be obtained, in low yield, by reaction either of an imido ester hydrochloride with hydrogen sulfide and pyridine, or of a Grignard reagent with a chlorothionocarbonate:

$$RC(:NHHCl)OR' + H_2S \xrightarrow{C_5H_5N} RCSOR' \longleftarrow ClCSOR' + RMgX$$

Amides (5). Thio amides may react in either the thiono form, $RC(:S)NH_2$, or the tautomeric thiol form, RC(:NH)SH, but normally seem to exist chiefly if not entirely in the thiono form.

Hot aqueous acids and alkalies generally hydrolyze thio amides and their *N*-substituted derivatives with moderate to considerable ease into the corresponding carboxylic acid, hydrogen sulfide, and ammonia or an amine. Concentrated sulfuric

acid, however, is likely in certain instances to effect cyclization, as in the case of monothiooxanilide to isatin (5). Alkaline hydrolysis of thiobenzamide leads to benzonitrile as an isolable intermediate.

Pyrolysis of thio amides yields hydrogen sulfide and a nitrile, the decomposition being somewhat easier than that of the analogous amide. Electrolytic or chemical reduction results in amines and thereby provides a route to important nitrogen bases, although aldehydes may also form under certain circumstances. Raney nickel desulfurization, especially effective for amine preparation:

$$RCSNR'R'' \xrightarrow{[H]} RCH_2NR'R''$$

can also be adapted to aldehyde preparation, *N*-substituted amides such as anilides (7), giving better yields than the unsubstituted. The outcome of oxidation reactions is more dependent on circumstances, and may result in any of several products.

Thio amides are weak acids and as such are converted by sodium alkoxides to sodium derivatives which can be alkylated. The *thioimido esters* thus formed are strongly basic, generally rather unstable, and yield thiol esters when hydrolyzed:

$$RCSNHR' \xrightarrow{NaOC_2H_5} [RC(:NR')S]^-Na^+ \xrightarrow{R''X} RC(:NR')SR'' \xrightarrow{H_2O} RCOSR''$$

The reaction between thio amides and halo carbonyl compounds constitutes the most widely used synthesis for thiazoles (20; see also Vol. **7**, p. 441).

Conversion of thio amides to the corresponding amides may be effected with agents such as mercuric or lead oxide:

$$RCSNH_2 + HgO \longrightarrow RCONH_2 + HgS$$

Ammonia and related substances give amidine-type products or *N*-substituted thio amides, depending upon the conditions:

$$RCSNHR' + NH_3 \longleftarrow RCSNH_2 + R'NH_2 \longrightarrow RC(:NR')NH_2 + H_2S$$

The thioformamido group eliminates hydrogen sulfide with an amino group ortho to it to form an imidazole under very mild conditions. This is valuable in nucleoside synthesis. The reaction of a thio amide with a nitrile results in an imido sulfide intermediate which may then yield a different thio amide and nitrile:

$$RCN + R'CSNH_2 \longrightarrow [RC(:NH)SC(:NH)R'] \longrightarrow R'CN + RCSNH_2$$

Thio amides may be quantitatively determined by means of hydrogen peroxide or iodine in alkaline solution (21).

The reactions most commonly used for the preparation of thio amides include:

(*1*) Hydrogen sulfide with nitriles (*q.v.*):

$$RCN + H_2S \longrightarrow RCSNH_2$$

This procedure seems to be the best and most generally used. An alcoholic solution containing a basic catalyst is usually used, sometimes with heating under pressure. The catalyst is frequently an amine, triethylamine in pyridine being especially promising (12).

(*2*) Phosphorus pentasulfide with amides:

$$5\,RCONH_2 + P_2S_5 \longrightarrow 5\,RCSNH_2 + P_2O_5$$

This method is also one of the most general, and is widely used; an alkaline sulfide is often added. Formation of the corresponding nitrile is a side reaction. Operation in

aromatic hydrocarbon solvents and rapid removal of the product from the by-products are advantageous. Thio lactams, which may be regarded as cyclic thio amides, can be formed in a similar way from lactams; their reduction provides a route to cyclic imines.

(*3*) Carbonyl compounds, as well as unsaturated compounds and certain other substances, with an amine and sulfur in the Kindler modification of the Willgerodt reaction (3):

$$RCOCH_3 + (CH_3)_2NH + S \longrightarrow RCH_2CSN(CH_3)_2$$

The reaction of sulfur with suitable amines also yields thio amides (23):

$$RCH_2NR'R'' + S \longrightarrow RCSNR'R''$$

(*4*) Thio acids (or derivatives such as their salts, esters, and amides) with ammonia or amines (14) (see also p. 64):

$$RCSOR' + R''NH_2 \longrightarrow RCSNHR''$$

(*5*) Aluminum trisulfide and ammonium salts of carboxylic acids:

$$3\,RCOONH_4 + Al_2S_3 \longrightarrow 3\,RCSNH_2 + 3\,H_2O + Al_2O_3$$

This reaction and the following one have been less frequently used, but show promise.

(*6*) Addition of organometallic compounds to isothiocyanates:

$$RMgX + R'NCS \longrightarrow RC(:NR')SMgX \xrightarrow{HCl} RCSNHR' + MgXCl$$

Some usefulness has been claimed for thio amides as pesticides, as films and filaments, and for prevention of corrosion. Several thio lactams have important physiological actions; for example, the thiobarbiturates (see *Barbituric acid and barbiturates*) and derivatives of 2-thiouracil, $S{:}C.NH.CO.CH{:}CH.NH$, which are antithyroid compounds (see *Thyroid and antithyroid preparations*) having among other uses the ability to effect economy in the fattening of animals.

Thioacetamide, CH_3CSNH_2, is a solid, which is easily soluble in water and alcohol, and less so in ether; various melting points have been reported in the range 107.5–116°C. It is a commercial product said to keep well in water solution, and the solution has been used advantageously as a substitute for hydrogen sulfide in inorganic analysis. Several thio amides also have specific analytical uses. These include rubeanic acid (dithiooxamide), $(CSNH_2)_2$, useful with several metal ions, especially copper, and also thioacetamide (bismuth) and thiobarbituric acid (rhodium); see also "Thiourea" under *Urea*.

Anhydrides and Acid Halides. *Thioacetic anhydride* (acetyl sulfide), $(CH_3CO)_2S$, is a colorless lacrimatory liquid which decomposes somewhat at its boiling point of 156–158°C., but can be distilled under reduced pressure. Raney nickel desulfurizes it to acetaldehyde. It is best prepared by refluxing thioacetic acid with acetyl chloride, but can also be obtained by the action of phosphorus pentasulfide on acetic anhydride or of acetyl chloride on lead thioacetate.

Thiobenzoic anhydride $(C_6H_5CO)_2S$, m.p. 48°C., results from the reaction of benzoyl chloride with sodium sulfide, as well as with hydrogen sulfide and pyridine at −20°C.

Diacetyl disulfide $(CH_3CO)_2S_2$, and *dibenzoyl disulfide* $(C_6H_5CO)_2S_2$, are obtainable from the thio acids by oxidation.

Thiobenzoyl chloride, C_6H_5CSCl, is obtainable by the action of thionyl or oxalyl chloride on dithiobenzoic acid. Although it reportedly reacts vigorously with aniline, it does not react in the expected way with amino acids.

Organic Dithio Acids

Dithio acids, RCSSH, are reddish-yellow oils of repulsive odor, which are unstable and decompose on standing. They are easily oxidized in air to solid stable disulfides, RC(:S)SSC(:S)R. *Dithioacetic acid*, CH_3CSSH, b_{15} 37°C., is difficultly soluble in water but easily so in organic solvents.

Dithio acids resemble monothio acids in the readiness with which they react with amines (see p. 60) but yield thio amides. The reaction of dithioformic acid or its potassium salt with amines at room temperature affords a preparation of thioformamides under very mild conditions; other aliphatic dithio acids react similarly. Dithiobenzoic acid, C_6H_5CSSH, is less reactive than the aliphatic dithio acids, however, and does not react with amino acids even on warming, although its carboxymethyl ester is effective.

Aliphatic dithio acids react readily with an isocyanate or isothiocyanate to form thioacylamino derivatives in good yield; for example:

$$HCSSH + C_6H_5NCO \longrightarrow HC(:S)NHC_6H_5 + COS$$

Dithio acids are usually prepared by reaction of a Grignard reagent with carbon disulfide:

$$RMgX + CS_2 \longrightarrow RCSSMgX \xrightarrow{H^+} RCSSH$$

Potassium dithioformate can be satisfactorily prepared from chloroform and potassium sulfide. The acid is best stored as this salt, because the free acid, a cream-colored powder, undergoes polymerization upon storage and diminishes rapidly in reactivity. Dithio acids are also obtainable from the reaction of an aldehyde with ammonium or sodium polysulfide.

Esters of aromatic dithio acids appear to be relatively stable toward water, in contrast to esters of dithioacetic acid and probably other aliphatic dithio esters, which soon undergo extensive decomposition. It has been suggested that the greater stability of the aromatic esters results from increased resonance contributions (1).

Dithio esters may be used for thioacylation:

$$RCSSR' + R''NH_2 \longrightarrow RCSNHR''$$

Thiocarbonic Acids

Although the thiocarbonic acids themselves are either unknown or very unstable, numerous derivatives are known. Their chemistry can often be anticipated from that of simple carbonates and thio acids.

Five possible thio acids are related to metacarbonic acid $(HO)_2CO$:

O ‖ HOCSH	S ‖ HOCOH	O ‖ HSCSH	S ‖ HOCSH	S ‖ HSCSH
Thiolcarbonic acid	Thionocarbonic acid	Dithiolcarbonic acid	Thionothiolcarbonic acid	Trithiocarbonic acid

Carbon disulfide (*q.v.*), CS_2, and carbonyl sulfide (carbon oxysulfide), COS (see Vol. **13**, p. 384), are related as anhydrides to some of the acids; in the same way thio-

phosgene, $CSCl_2$ (see Vol. **13,** p. 386), is an acid chloride and thiourea, $CS(NH_2)_2$ (see *Urea*), a diamide with respect to more than one acid.

Three monoamides of thiocarbonic acids are theoretically possible: thiolcarbamic acid, NH_2COSH; thionocarbamic acid, NH_2CSOH; and dithiocarbamic acid, NH_2CSSH. The dithio acid has been known to exist but it is not very stable. The hydrazide of thionocarbamic acid is thiosemicarbazide, $NH_2CSNHNH_2$ (see Vol. **7,** p. 587). Organic thiocyanates (*q.v.*) and isothiocyanates, which can be made by the reaction of thiophosgene with primary amines, are the acid anhydrides of the thiocarbamic acid series (see p. 66).

Dithizone (phenylazothionoformic acid phenylhydrazide, diphenylthiocarbazone), $C_6H_5N{=}NCSNHNHC_6H_5$, is extremely useful in inorganic analysis. Many metallic ions form characteristic intensely colored complexes with it, and under proper conditions excellent selectivity and sensitivity can often be achieved (see *Lead,* Vol. 8, p. 218). A solution of dithizone in chloroform or carbon tetrachloride is usually shaken with an aqueous solution of the metallic salt, and the resulting dithizone complex is extracted into the organic solvent and determined colorimetrically or otherwise.

Esters of the mono-, di-, and trithio acids can be made by using mercaptans or alcohols with phosgene or thiophosgene, or chloroformates or thiochloroformates (see Vol. 8, p. 861). Glycolic acid esters of thiocarbonic and thiocarbamic acids have been suggested for use as waving solutions (see Vol. **12,** p. 240).

MONOTHIOCARBONIC ACIDS

Monothiolcarbonates, RSCOOR, are easily hydrolyzed to mercaptans, alcohols, and carbon dioxide; bases are seemingly more effective catalysts than are acids. Sulfides may also form at high temperatures. In addition to the general method of preparing thiolcarbonates, diethyl thiolcarbonate is obtainable from ethylxanthates as shown:

$$\left.\begin{matrix} C_2H_5OCSSR \\ \text{or} \\ COS \end{matrix}\right\} \xrightarrow{\text{alc. KOH}} KSCOOC_2H_5 \xrightarrow{C_2H_5X} C_2H_5SCOOC_2H_5 \xleftarrow{C_2H_5SNa} ClCOOC_2H_5$$

Diaryl **thionocarbonates** rearrange at about 300°C. to the isomeric thiol esters:

$$(ArO)_2C{:}S \longrightarrow ArOC(:O)SAr$$

This reaction makes possible a promising conversion of phenols to thiophenols (18). Thionocarbonate esters may be prepared by the reaction of thiophosgene with an alkoxide, or with a phenol in the presence of a base.

Thiolcarbamates can be very satisfactorily prepared by the reaction of organic thiocyanates with concentrated sulfuric acid:

$$RSCN + H_2O \xrightarrow{H_2SO_4} RSOCNH_2$$

DITHIOCARBONIC ACIDS

The reaction of phosgene and a mercaptide provides a route to **esters of dithiolcarbonic acid** $(HS)_2CO$. These are subject to hydrolysis in much the same way as the monothiolcarbonates.

The other possible dithio acid is **thionothiolcarbonic acid,** HOCSSH, or xanthic

acid (see *Xanthic acid and xanthates*). Xanthates are cleaved by phenylhydrazine more easily than are dithiolcarbonates and may be distinguished in this way (18):

$$ROCSSR' + C_6H_5NHNH_2 \longrightarrow ROCSNHNHC_6H_5 + R'SH$$

In some instances, xanthates tend to rearrange to dithiolcarbonates upon being heated.

The reaction of carbon disulfide, ethyl alcohol, and potassium hydroxide, yielding potassium ethylxanthate, C_2H_5OCSSK, also illustrates a type of reaction which is very important in the xanthate (viscose) process for manufacturing rayon (see Vol. **11**, p. 529) and cellophane (*q.v.*).

Dithiocarbamic acid can be isolated from its ammonium salt, but it is not very stable. Its esters (dithiourethans), NH_2CSSR, decompose on distillation into RSH and HNCS, although the completely substituted compounds, R_2NCSSR', are relatively stable.

Salts of dithiocarbamic acid or its derivatives are obtained from carbon disulfide with ammonia or a primary or secondary aliphatic amine:

$$R_2NH + CS_2 \longrightarrow [R_2NC(:S)S]^- R_2NH_2^+$$

Aromatic amines do not yield stable salts unless a stronger base is present, and tend to give thiourea derivatives. Use of alkali in the reaction with the amine results in an alkali metal dithiocarbamate.

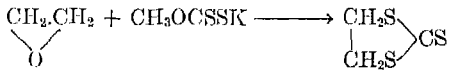
Ammonium dithiocarbamate is useful in the synthesis of heterocyclic compounds (*q.v.*; see also ref. 20), and several such dithiocarbamates are also used in inorganic analysis, the most important probably being sodium diethyldithiocarbamate, $(C_2H_5)_2NCSSNa$, which is used for the determination of small amounts of copper (22). Dithiocarbamic acid derivatives have important commercial uses, as do the thiuram disulfides $(R_2NCS)_2S_2$, derived from them by mild oxidation with hydrogen peroxide, nitrous acid, iodine, and similar agents (see *Fungicides, agricultural*; *Rubber chemicals*). A wide variety of other dithiocarbamates are known (4).

TRITHIOCARBONIC ACID

Trithiocarbonic acid $(HS)_2CS$, is obtained as an unstable reddish oil, which is slightly soluble in water and in organic solvents, by careful treatment of an alkali salt with concentrated hydrochloric acid. The alkali salts may be prepared in turn from carbon disulfide with alkali sulfides or hydrosulfides (RSCSSNa is obtained with RSNa; see *Mercaptans*, Vol. 8, p. 861).

Sodium trithiocarbonate, Na_2CS_3, is a deliquescent pinkish-yellow solid, which gives the distinctly red aqueous solution apparently characteristic of true trithiocarbonates. It undergoes only very slow decomposition to sodium sulfide and sodium carbonate in excess alkali, but is decomposed by moist air and by even a weak acid. It may be obtained, in addition to the general preparation mentioned above, along with sodium carbonate, by the reaction of carbon disulfide and sodium hydroxide. As a result of this reaction, and also possibly because of formation from the sodium sulfide present, sodium trithiocarbonate is the chief by-product in the xanthation of cellulose (see *Rayon*, Vol. **11**, p. 530).

The *potassium salt* is used for the analysis of nickel, osmium, and thallium. Its alkylation yields trithiocarbonic **esters** $(RS)_2CS$, which hydrolyze readily especially in the presence of a base. The reaction of epoxides with xanthates also yields these esters, generally in good yield:



The trithiocarbonates react with one molar equivalent of ammonia or a primary or secondary amine to yield a dithiourethan:

$$(RS)_2CS + R_2'NH \longrightarrow RSSCNR_2' + HSR$$

The fate of the urethan upon further treatment with the same base is variable. Thus, ammonium thiocyanate and a mercaptan result with ammonia, and symmetrically disubstituted thioureas with primary amines. With secondary amines, however, the reaction does not proceed readily beyond the urethan stage.

Bibliography

(1) Knight, S. B., Bost, R. W., Shealy, O. L., and Williams, J. P., *J. Am. Chem. Soc.*, **73**, 29 (1951).
(2) Brown, R., Jones, W. E., and Pinder, A. R., *J. Chem. Soc.*, **1951**, 2123.
(3) Carmack, M., and Spielman, M. A., "The Willgerodt Reaction," in Adams, *Organic Reactions*, Wiley, N.Y., 1946, Vol. III, pp. 83–107.
(4) Chabrier, P., and Nachmias, G., *Bull. soc. chim.* (*France*), **1950**, D51.
(5) Chabrier, P., and Renard, S. H., *Bull. soc. chim.* (*France*), **1949**, D272.
(6) Connor, R., "Organic Sulfur Compounds," in Gilman, *Organic Chemistry*, Wiley, N.Y., 1943, Vol. I, pp. 929–43.
(7) Cronyn, M. W., and Goodrich, J. E., *J. Am. Chem. Soc.*, **74**, 3936 (1952).
(8) Cronyn, M. W., and Jiu, J., *J. Am. Chem. Soc.*, **74**, 4726 (1952).
(9) Crouch, W. W., *J. Am. Chem. Soc.*, **74**, 2926 (1952).
(10) Ellingboe, E. K., *Organic Syntheses*, Wiley, N.Y., 1951, Vol. 31, p. 105.
(11) Ephraim, F., *Inorganic Chemistry*, 5th English ed. by P. C. L. Thorne and E. R. Roberts, Gurney and Jackson, London, 1948, pp. 548–50, 553.
(12) Fairfull, A. E. S., Lowe, J. L., and Peak, D. A., *J. Chem. Soc.*, **1952**, 742.
(13) Hawkins, P. J., Tarbell, D. S., and Noble, P., Jr., *J. Am. Chem. Soc.*, **75**, 4462 (1953).
(14) McOmie, J. F. W., *Ann. Rep. on Progr. Chem.* (*Chem. Soc., London*), **XLV**, 207 (1948).
(15) Schwyzer, R., *Helv. Chim. Acta*, **36**, 414 (1953).
(16) Sheehan, J. C., and Johnson, D. A., *J. Am. Chem. Soc.*, **74**, 4726 (1952).
(17) Sjöberg, B., *Svensk Kem. Tidskr.*, **63**, 90–94 (1951); *C.A.*, **47**, 8640.
(18) Tarbell, D. S., and Harnish, D. P., *Chem. Revs.*, **49**, 45–64 (1951).
(19) Noble, P., Jr., and Tarbell, D. S., *Organic Syntheses*, Wiley, N.Y., 1952, Vol. 32, p. 101.
(20) Wiley, R. H., England, D. C., and Behr, L. C., "The Preparation of Thiazoles," in Adams, *Organic Reactions*, Wiley, N.Y., 1951, Vol. VI, pp. 367–409.
(21) Wojahn, H., and Wempe, E., *Arch. Pharm.*, **285**, 375 (1952); *C.A.*, **47**, 12126.
(22) Zuehlke, C. W., *Organic Chemical Bull.*, **24**, No. 1, 4 (1952), Eastman Kodak Co., Rochester, N.Y.
(23) U.S. Pat. 2,560,296 (July 10, 1951), C. L. Levesque (to Rohm and Haas Co.).

LAMAR FIELD

THIO ALCOHOLS, RSH. See *Mercaptans.*

THIOALDEHYDES, RCHS. See *Sulfur compounds, organic,* Vol. **13,** p. 442.

THIOAURIN. See *Streptomyces antibiotics* (*survey*), Vol. **13,** pp. 59, 63, 64.

THIOBETAINES, $R_2S.O.CO.CH_2$. See *Sulfur compounds, organic,* Vol. **13,** p. 442.

THIOCARBANILIDE $(C_6H_5NH)_2CS$. See *Urea* (*derivatives*).

THIOCARBONIC ACIDS; THIOCARBONATES. See *Thio acids.*

THIOCHROME, $C_{12}H_{14}N_4OS$. See *Thiamine.*

6,8-THIOCTIC ACID, $S.S.CH_2.CH_2.CH(CH_2)_4COOH$. See *Sulfides, organic*, Vol. **13**, p. 296.

THIOCYANATES, INORGANIC. See *Cyanides (thiocyanates)*, Vol. **4**, p. 736.

THIOCYANATES AND ISOTHIOCYANATES, ORGANIC

Organic thiocyanates, which are esters of thiocyanic acid, $HSC{\equiv}N$ (see Vol. **4**, p. 737), are compounds in which a thiocyano (thiocyanato) group, $-SC{\equiv}N$, is attached to an organic radical. Similarly, the organic isothiocyanates (thiocarbimides, "mustard-oils") contain an isothiocyano (isothiocyanato) group, $-N{=}C{=}S$, attached to an organic radical and may be considered esters of isothiocyanic acid, $HN{=}C{=}S$. According to Beilstein, ethyl thiocyanate, made in 1845, was the first recorded compound of this class, and the first mention of an isothiocyanate was in 1835. Beilstein lists a total of approximately three hundred thiocyanates and one hundred isothiocyanates.

Organic thiocyanates apparently do not occur in nature. The most common naturally occurring isothiocyanate, allyl isothiocyanate ("mustard oil"), exists as its glucoside, potassium myricate, $CH_2{=}CHCH_2N{=}C(SC_6H_{11}O_5)OSO_2OK$, in plants of the mustard family. Isopropyl, crotonyl, *sec*-butyl, phenyl, benzyl, *p*-hydroxybenzyl, and *β*-phenylethyl (phenethyl) isothiocyanates and cheiroline, $CH_3SO_2(CH_2)_3NCS$, erysoline, $CH_3SO_2(CH_2)_4NCS$, and sulforaphene, $CH_3S(O)CH{=}CHCH_2CH_2NCS$, have also been isolated from plant material. Thiocyanates were the first synthetic organic contact insecticides to achieve commercial importance and were introduced in 1932 (13); their principal uses continue to be in the pesticide field. Isothiocyanates are not widely used commercially. See also *Cyanides and cyanogen compounds*; *Phosgene (organic isocyanates)*.

Properties

CONSTANTS

Some physical properties of a number of thiocyanates and isothiocyanates are listed in Table I.

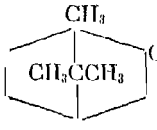
REACTIONS

Organic thiocyanates and isothiocyanates undergo a variety of reactions that are useful in laboratory syntheses, analyses, and characterization. The following discussion is based on the organic thiocyanates, with references to the isothiocyanates wherever appropriate. Several review articles on this subject have been published (12,18).

Reactions in which the SCN Group Acts as a Halogenoid. The term halogenoid has been used to designate any univalent chemical aggregate composed of two or more electronegative atoms, that shows in the free state certain characteristics of the halogens and that combines with hydrogen to form an acid and with silver to form a salt insoluble in water (17). The first halogenoid which was isolated (by Soderback in 1919) was thiocyanogen. It would be expected, therefore, that certain reactions of thiocyanates would resemble those of the corresponding halides. The following exemplify this.

Replacement of SCN. The decomposition of thiocyanates with alcoholic solutions

TABLE I. Physical Properties of Some Thiocyanates and Isothiocyanates.

Compound	M.p., C.	B.p., C.	n_D	Sp.gr.
		Thiocyanates		
CH_3SCN		130.5^{765}	1.4685^{20}	1.0744_4^{20}
C_2H_5SCN		145.5^{765}	1.4630^{20}	1.0116_4^{20}
n-C_3H_7SCN		164.5	1.4631^{20}	0.9817_4^{20}
iso-C_3H_7SCN		150		
$CH_2{=}CHCH_2SCN$		161		1.056_4^{15}
n-C_4H_9SCN		$184.^{770}$	1.4639^{20}	0.9610_4^{20}
iso-C_4H_9SCN		175.4		
n-$C_5H_{11}SCN$		91^{16}	1.4620^{25}	
$C_{12}H_{25}SCN$ (Lorol)		$154–56^{2.5}$		
n-$C_{16}H_{33}SCN$		$242–49^{30}$		
$C_{12}H_{25}COOCH_2CH_2SCN$[a] (Lethane 60)[b]		$160–90^{0.1}$	1.4692^{20}	0.976^{20}
$C_4H_9OCH_2CH_2OCH_2CH_2SCN$ (Lethane 384)[c]		$120–25^{0.25}$	1.4657^{20}	1.021^{20}
 $OOCCH_2SCN$[c] (Thanite)		$138–57^{0.5}$		
$(—CH_2SCN)_2$	90–90.5			
$O(CH_2CH_2SCN)_2$ (Lethane A-70)		$140–150^{25}$	1.5298^{25}	
C_6H_5SCN		121^{35}		
$C_6H_5CH_2SCN$	43–43.5			
p-ClC_6H_4SCN	35–36			
p-HOC_6H_4SCN	53–54			
2,4-$(NO_2)_2C_6H_3SCN$ (Nirit)	139			
p-$H_2NC_6H_4SCN$	57–57.5			
p-$(CH_3)_2NC_6H_4SCN$	73–74			
p-$C_6H_4(SCN)_2$	108.5			
		Isothiocyanates		
CH_3NCS		119^{750}	1.5258	$1.069^{37.2}$
C_2H_5NCS		$131.5–32^{765}$	1.5142^{18}	1.003^{18}
n-C_3H_7NCS		152.7^{713}	1.5085^{16}	0.978^{16}
$CH_2{=}CHCH_2NCS$		150	1.5298^{15}	1.016^{15}
n-C_4H_9NCS		$164.5–65.3^{724}$		
n-$C_5H_{11}NCS$		193.4		
$C_6H_5CH_2NCS$		125^{11}		
C_6H_5NCS		222^{762}	$1.6492^{23.4}$	$1.1280^{23.4}$
p-ClC_6H_4NCS	45–47	249–50		
p-$NO_2C_6H_4NCS$	112–13			
p-$C_6H_4(NCS)_2$	130			
1-$C_{10}H_7NCS$	58			

[a] The radical $C_{12}H_{25}$ represents an average.
[b] The commercial product is a 50% solution in refined kerosine.
[c] Isobornyl thiocyanoacetate.

of alkali sulfides is well known and has been used as a quantitative method of analysis (5).

$$2\,RSCN + Na_2S \longrightarrow R_2S + 2\,NaSCN$$

The SCN group can also be replaced with an amino group. Although the reaction of thiocyanates with amines generally takes another course (see p. 71), the following is

an example of a replacement in which the halogenoid character of the thiocyanate is shown (4):

$$2,4\text{-}(NO_2)_2C_6H_3SCN + C_6H_5NH_2 \longrightarrow 2,4\text{-}(NO_2)_2C_6H_3NHC_6H_5 + HSCN$$

Quaternization:

$$R_3N + RSCN \longrightarrow [R_4N]^+SCN^-$$

This reaction proceeds best with those thiocyanates in which the SCN group is quite labile, for example, benzyl thiocyanate. In quaternizations with 2-chloroethyl thiocyanate, compounds of the type $[R_3NCH_2CH_2SCN]^+Cl^-$ are obtained.

Isothiuronium Salt Formation. The more reactive thiocyanates, for example, benzyl and allyl thiocyanates, react with thiourea to give the isothiuronium (thiuronium) salts.

$$(NH_2)_2CS + RSCN \longrightarrow [NH_2C(SR)=NH_2]^+SCN^-$$

Effect on Orientation in the Benzene Ring. The nitration of aromatic thiocyanates has been the subject of several studies. Phenyl thiocyanate gives a mixture of the *o*- and *p*-nitro derivatives. However, the *o*-,*p*-directing influence of the SCN group, like that of the halogens, is less than that of the methyl group (4).

Compounds Analogous to Sulfenyl Halides. Compounds of the type RSCl have their counterpart in RSSCN. Sulfur thiocyanates, $S(SCN)_2$ and $S_2(SCN)_2$, have also been described. The addition of arenesulfenyl thiocyanates, ArSSCN, to olefins, for example, cyclohexene, has been studied recently (10). The reaction of RSSCN with mercaptans and thiophenols to give disulfides, RSSR′, and thiocyanic acid has also been studied.

Compounds Analogous to Acid Halides. Mixed anhydrides of organic acids and thiocyanic acid, for example, RC(O)SCN and $R_2NC(S)SCN$, are known but are usually less stable than the corresponding acid chlorides. As a rule, they react as if rearranged to the isothiocyanates, for example:

$$RC(O)NCS + R'OH \longrightarrow RC(O)NHC(S)OR'$$

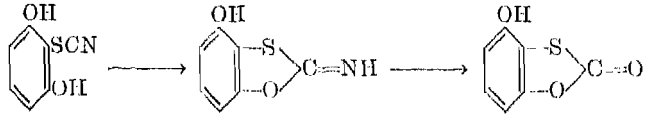
Compounds Analogous to Chloramines. A few compounds of the type RNHSCN and R_2NSCN are known. They are prepared by thiocyanation of the aliphatic amines.

Reactions Involving the CN Group. These are the more characteristic reactions of organic thiocyanates.

Reaction with Alcohols. Thiocyanates react with alcoholic hydrochloric acid to give intermediates which are hydrolyzed to thiocarbamates:

$$RSCN + R'OH + HCl \longrightarrow RSC(OR')=NH.HCl \longrightarrow RSCONH_2 + R'Cl$$

If the hydroxyl group is properly substituted in the same molecule, ring closure may occur. This is well known for α-thiocyano ketones (enol form), 2-thiocyanoethanol, $HOCH_2CH_2SCN$, and *o*-thiocyano phenols, for example:



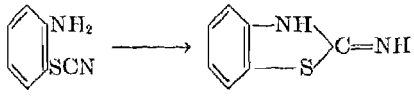
The addition of alcohols to isothiocyanates gives *N*-substituted thiocarbamates:

$$RNCS + R'OH \longrightarrow RNHCSOR'$$

Reaction with Amines (see also p. 69). Primary and secondary amines react with thiocyanates to give alkyl- or arylthioformamidines:

$$RSCN + R'NH_2 \longrightarrow RSC(=NH)NHR'$$

Under certain conditions the basicity of the amine can convert the thiocyanate to the corresponding disulfide as shown below for alkalies. If the NH_2 is properly substituted in the molecule containing the SCN, ring closure to the thiazole results, for example:



The addition of primary and secondary amines to isothiocyanates to give substituted thioureas is probably the best-known reaction of isothiocyanates:

$$RNCS + R_2NH \longrightarrow RNHCSNR_2$$

Reaction with Alkalies. Most thiocyanates are converted to disulfides by means of alcoholic alkali:

$$2\,RSCN + 2\,NaOH \longrightarrow RSSR + NaCN + NaCNO + H_2O$$

It is interesting to note that an aqueous solution of sodium thiocyanoacetate, $NCSCH_2COONa$, is stable to long heating. Sodium ethoxide in alcohol solution reacts with phenyl thiocyanate to give sodium thiophenoxide, C_6H_5SNa, ethyl phenyl sulfide, and diphenyl disulfide. The mustard oils are hydrolyzed in aqueous alkali and also by strong acids to the corresponding amines:

$$RNCS \xrightarrow{H_2O} RNH_2$$

Reduction. The reduction of a thiocyanate to the mercaptan is a well known but little used reaction. Zinc–hydrochloric acid and zinc–sodium carbonate have given good yields:

$$RSCN + H_2 \longrightarrow RSH + HCN$$

Reduction of an isothiocyanate regenerates the parent amine.

Oxidation. Under somewhat vigorous conditions (for example, with nitric acid) organic thiocyanates are oxidized to the corresponding sulfonic acids:

$$RSCN \xrightarrow{(O)} RSO_3H$$

In certain cases intermediate products can be isolated, for example benzyl thiocyanate has been oxidized with chlorine to $C_6H_5CH_2S(O)CN$.

Reaction with Halogens. Some study has been given to the following reaction:

$$RSCN + 3\,Cl_2 + 2\,H_2O \longrightarrow RSO_2Cl + ClCN + 4\,HCl$$

Aliphatic thiocyanates form sulfonyl chlorides in this manner more readily than aromatic ones. Halogenation of isothiocyanates normally proceeds as follows:

$$RNCS + 2\,Cl_2 \longrightarrow RNCCl_2 + SCl_2$$

Reactions with Grignard Reagents. The following equations represent the usual course of the reactions with Grignard reagents:

$$RSCN + R'MgBr \longrightarrow RSR' + MgBrCN$$

$$RSCN + R'MgBr + HBr \longrightarrow RSH + R'CN + MgBr_2$$

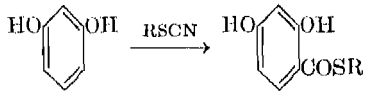
$$RNCS + CH_3MgBr \longrightarrow RNHC(S)CH_3$$

Addition of Hydrogen Sulfide. Reactions with hydrogen sulfide have not been studied extensively but are reported to be as follows:

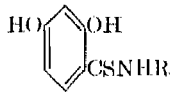
$$RSCN + H_2S \longrightarrow RSCSNH_2$$

$$RNCS + H_2S \longrightarrow (RNH)_2CS$$

Reactions with Polyphenols. Under the experimental conditions of the *Hoesch synthesis*, thiocyanates give thio esters, for example (16):



In the same reaction isothiocyanates give amides of thio acids, for example:



Miscellaneous Reactions. *Reactions with Thiocarboxylic Acids.* Thiobenzoic acid, for example, reacts with:

(1) alkyl thiocyanates to give *N*-benzoyldithiocarbamates:

$$C_2H_5SCN + C_6H_5COSH \longrightarrow C_6H_5CONHCSSC_2H_5$$

(2) aryl thiocyanates to give thiol esters:

$$C_6H_5SCN + C_6H_5COSH \longrightarrow C_6H_5COSC_6H_5 + HSCN$$

(3) isothiocyanates to give benzamides:

$$RNCS + C_6H_5COSH \longrightarrow RNHCOC_6H_5 + CS_2$$

Thiobenzoic acid has been used as a reagent for differentiating these three types of compounds.

Rearrangement of Thiocyanates to Isothiocyanates. Allyl thiocyanates and analogous compounds rearrange readily at elevated temperatures. Alkyl thiocyanates rearrange only upon prolonged heating at high temperatures, and aryl thiocyanates are thermally stable (18).

Polymerization. Thiocyanates do not polymerize readily. The lower alkyl thiocyanates have been polymerized at high temperatures in the presence of a trace of hydrogen chloride to the trialkyl thiocyanurates (12). The isothiocyanates can polymerize in a manner similar to isocyanates, but less readily. Ethylene diisothiocyanate, however, polymerizes very readily at room temperature.

Unique Reactions of Isothiocyanates. The addition of certain alkali salts to isothiocyanates gives, after acidification, the following products:

$$ArNCS + KCN \xrightarrow{H^+} ArNHC(S)CN$$

$$RNCS + Na_2NCN \xrightarrow{H^+} RNHC(S)NHCN$$

$$ArNCS + NaCH(COOC_2H_5)_2 \xrightarrow{H^+} ArNHC(S)CH(COOC_2H_5)_2$$

Analytical Methods

The following are the most common methods for the qualitative analysis of thiocyanates (5): (*1*) heating with alcoholic potassium hydroxide and testing for cyanide

ion; (*2*) heating with alcoholic sodium sulfide and testing for thiocyanate ion; (*3*) treating with thiobenzoic acid to give a solid derivative.

The most common derivatives of an isothiocyanate are the thioureas made by reaction with ammonia or amines.

The official method (8) for quantitative determination of thiocyanates as used by the A.O.A.C. is known as the *Elmore method.* This involves reaction of the organic thiocyanate with an aqueous mixture of potassium disulfide, sodium sulfide, and potassium hydroxide. The resulting thiocyanate radical is converted to cuprous thiocyanate and analyzed for nitrogen by the Kjeldahl method. Apparently no specific method has been devised for the determination of isothiocyanates.

Preparation and Manufacture

Several review articles have been written on this subject (2,6,7,9,14,18).

THIOCYANATES

Preparation of Aliphatic Thiocyanates. *Reaction of Alkyl Halides with Inorganic Thiocyanates.* The most common method for preparing a thiocyanate is the reaction of an organic halide with an inorganic thiocyanate:

$$RX + MSCN \longrightarrow RSCN + MX$$

Conditions vary with the reactivity of the halide, for example, the reaction proceeds in alcohol with chloroacetone at room temperature; 5 hours' refluxing in aqueous alcohol is required with benzyl chloride; 12 hours' refluxing in water with 2-butoxy-2′-chlorodiethyl ether, $C_4H_9OCH_2CH_2OCH_2CH_2Cl$; and 24 hours' refluxing in methyl isobutyl ketone with 2-chloroethyl esters, $RCOOCH_2CH_2Cl$. Copper powder or sodium bromide or iodide may be used as catalyst. The method fails for certain 2,3-dihalides or tertiary halides in which the halogen behaves like free halogen to give only the thiocyanogen polymers. In other cases isothiocyanates may be formed (see p. 75).

Reaction of Alkyl Sulfates or Sulfonates with Inorganic Thiocyanates:

$$(RO)_2SO_2 + 2\ MSCN \longrightarrow 2\ RSCN + M_2SO_4$$

$$ArSO_3R + MSCN \longrightarrow RSCN + ArSO_3M$$

Reaction of Organic Sulfides or Mercaptides with Cyanogen Bromide:

$$RSR + BrCN \longrightarrow RSCN + RBr$$

$$RSM + BrCN \longrightarrow RSCN + MBr$$

This method has been extended to thiophenols, mercapto heterocyclic compounds, and thio acids.

Addition of Thiocyanogen to Olefins:

$$—CH{=}CH— + (SCN)_2 \longrightarrow —CH(SCN)CH(SCN)—$$

The scope and limitations of the addition of thiocyanogen to unsaturated compounds and its use to prepare *N*-thiocyano compounds has been carefully reviewed (18). The reaction is best known for addition to olefins to give the corresponding dithiocyanates, and a method of analysis known as the *thiocyanogen value* has been based on this (see Vol. 6, pp. 156, 229).

The Addition of Thiocyanic Acid to Olefins:

$$—CH{=}CH— + HSCN \longrightarrow —CH_2CH(SCN)—$$

The olefin and an aqueous solution of an alkaline thiocyanate are stirred and a mineral acid slowly added. If the olefin is not readily reactive the thiocyanic acid which is generated is converted to perthiocyanic acid, $H_2S_3C_2N_2$. In many cases the isothiocyanates are formed (see p. 75).

Preparation of Aromatic Thiocyanates. *Thiocyanation of Aromatic Nuclei.* The direct replacement of a hydrogen atom by a thiocyano group is commonly termed thiocyanation. This reaction has been applied to aromatic compounds possessing an activated nuclear position, such as primary, secondary, and tertiary amines of the benzene, naphthalene, and anthracene series; phenols of the benzene and naphthalene series; and a few hydrocarbons and heterocyclic compounds such as anthracene, benzanthracene, and pyrrole (18). Free thiocyanogen or even thiocyanogen chloride, ClSCN, may, of course, be used, but the more general practice is to use thiocyanogen generated in the solution in one of several ways: (*1*) by the action of chlorine or bromine on a metallic thiocyanate, preferably in a neutral solvent such as alcohol; (*2*) by the use of *N*-chloroamides on metallic thiocyanates; (*3*) by the use of cupric thiocyanate: $2\ Cu(SCN)_2 \rightarrow 2\ CuSCN + (SCN)_2$; (*4*) by the action of hydrogen peroxide on thiocyanic acid; and (*5*) by the electrolytic oxidation of an inorganic thiocyanate.

Replacement of Diazonium Groups with SCN (Sandmeyer Reaction). The replacement of a diazotized NH_2 group with SCN by means of cuprous thiocyanate gives satisfactory results:

$$C_6H_5N_2{}^+Cl^- + CuSCN \longrightarrow C_6H_5SCN + N_2 + CuCl$$

Reaction of Sulfenyl Compounds with Cyanides:

$$RSSO_3Na + NaCN \longrightarrow RSCN + Na_2SO_3$$

$$RSCl + NaCN(\text{or } HCN) \longrightarrow RSCN + NaCl\ (\text{or } HCl)$$

These methods have been largely used for the preparation of aromatic thiocyanates since the starting materials are more generally available for these. However, certain aliphatic thiocyanates have also been made this way, for example, trichloromethyl thiocyanate, Cl_3CSCN.

Manufacture of Thiocyanates. The commercial organic thiocyanates (given with their trade names) in Table I (see also Vol. 7, p. 899) are all made by the metathetical reaction between an organic halide and a metallic thiocyanate. The process for Lethane 60 is described as an example of industrial practice.

In a typical run, a mixture of 7,000 lb. of coconut oil fatty acid and a 30% excess of phosphorus trichloride was treated at room temperature. The bottom layer of phosphorous acid was drawn off. A 3–4% excess of ethylene oxide was added to the top layer. The mixture was warmed to 150°C. and concentrated under vacuum to give about 9000 lb. (98–99% yield) of chloroethyl "coconate." A mixture of 5250 lb. of this ester with a 20% excess of anhydrous technical sodium thiocyanate was adjusted to a pH of below 7 with niter cake and then heated with agitation at 128°C. for 20–30 hours to effect the conversion to the thiocyanoethyl coconate. The course of the reaction was followed by refractometry. When the conversion was complete, the mixture was diluted with press-wash-refined kerosine and washed three times with water, brine being added when necessary to effect a clean separation. The organic layer was then decolorized by treatment with carbon for an hour at 85°C. and passed through a filter press. The press cake was washed with kerosine and the recovered washings (press-wash kerosine) were used in the next batch. The decolorized product

was concentrated under vacuum to remove volatile impurities, refiltered to remove last traces of solids, and finally diluted with refined kerosine to 50% vol./vol. to produce about 1000 gal. of Lethane 60.

ISOTHIOCYANATES

Decomposition of Dithiocarbamates. A common method of preparation is the conversion of the dithiocarbamate derived from a primary amine to its heavy-metal salt (for example, the lead, copper, iron, or zinc salt) and heating the salt to the decomposition point:

$$RNHCSSM \longrightarrow RNCS + MHS$$

It is often more convenient to treat an alkaline dithiocarbamate of a primary amine with an alkoxycarbonyl chloride (a chloroformic ester) and then thermally decompose the product. The latter decomposes at a lower temperature than the metal salts and the reaction proceeds more smoothly.

$$RNHCSSM + ClCOOR \longrightarrow RNHCSSCOOR \xrightarrow{heat} RNCS + COS + ROH$$

Reaction of Amines and Thiophosgene (Thiocarbonyl Chloride). Amines react with thiophosgene to give isothiocyanates:

$$RNH_2 + CSCl_2 \longrightarrow RNCS + 2\,HCl$$

Cleavage of thioureas. Aromatic isothiocyanates have been made by the action of various agents (iodine, phosphorus pentoxide, acetic anhydride, hydrochloric acid, phosphoric acid, dilute sulfuric acid) on symmetrical diarylthioureas:

$$(ArNH)_2CS \xrightarrow{I_2} ArNCS$$

Rearrangement of Thiocyanates. Thermal rearrangement of thiocyanates gives isothiocyanates; zinc chloride may be used as a catalyst:

$$RSCN \xrightarrow{heat} RNCS$$

This method works best with allylic thiocyanates, and allyl isothiocyanate itself is so produced on a limited scale. In some cases, the isothiocyanate is the product isolated from the reaction of an organic halide with a metallic thiocyanate. However, no general rule is applicable, for example:

$$2,4\text{-}(NO_2)_2C_6H_3Cl + MSCN \longrightarrow 2,4\text{-}(NO_2)_2C_6H_3SCN + MCl$$

$$2,4,6\text{-}(NO_2)_3C_6H_2Cl + MSCN \longrightarrow 2,4,6\text{-}(NO_2)_3C_6H_2NCS + MCl$$

Addition of Thiocyanic Acid to Olefins. In some reactions in which thiocyanic acid is generated from a metallic salt in the presence of an olefin, an isothiocyanate is obtained in which the —NCS group is attached to the most highly substituted carbon atom. The reaction gives the isothiocyanate exclusively when tertiary olefins having 6–9 carbon atoms are used:

$$R_2C{=}CH_2 \longrightarrow R_2C(NCS)CH_3$$

Lower olefins give a mixture of thiocyanate and isothiocyanate; higher olefins, which may contain both reactive and unreactive double bonds, give low yields. Other olefins which contain actived double bonds, such as dicyclopentadiene, styrene, and mesityl oxide, usually give good yields of the isothiocyanates.

Addition of Sulfur to Isocyanides. The isocyanides, RNC (see Vol. 9, p. 372) and sulfur react above 100°C. to form isothiocyanates.

Toxicology

The oral toxicity of the alkyl thiocyanates as measured in rats decreases as the series is ascended, ranging from an LD_{50} of 60 mg./kg. for the methyl analog to 1250 mg./kg. for the lauryl compound. The commercial thiocyanates that are used in fly sprays have low oral toxicities with LD_{50}'s of 400–1250 mg./kg. They are dangerous, however, when applied to the skin in doses of 500 mg./kg. The aliphatic thiocyanates are paralytic poisons acting on the central nervous system. The lower homologs release hydrogen cyanide in the body, thus giving a cyanide effect. Since thiocyanate ion appears in the urine as a detoxification product of cyanide, it is considered that the body can excrete sublethal doses of thiocyanates (3).

The isothiocyanates in general are toxic and are irritating to the skin. 1-Naphthyl isothiocyanate caused an outbreak of dermatitis (15), and repeated administration to guinea pigs both by injection and by feeding caused liver damage (11).

Uses

Many examples of the usefulness of organic thiocyanates as solvents, antioxidants, and anticorrosives are given in the patent literature. Cyanomethyl, methylene, ethylene, and trimethylene thiocyanates are claimed as solvents for polyacrylonitrile (25). Organic thiocyanates in photographic processing solutions are also stated to increase the rate of penetration of a polyvinyl resin photographic layer. Alkyl thiocyanates are described as stabilizers for chlorinated hydrocarbons, thiocyanoacetone is stated to inhibit the deterioration of paper, and alkyl and aryl thiocyanates are soap preservatives. Butyl thiocyanate, triphenylmethyl thiocyanate, and 1-naphthyldiphenylmethyl thiocyanate stabilize lubricants against oxidation (23). Various halogenated organic thiocyanates are also stated to help lubricants withstand extreme pressures. Alkyl, aryl, and aralkyl thiocyanates protect metallic surfaces against acid in both degreasing and pickling operations (20).

Nitro-substituted aromatic thiocyanates are stated to modify the emulsion polymerization of, for example, butadiene-styrene. Compounds such as stearamidomethyl thiocyanate (*N*-thiocyanomethylstearamide) and *N,N'*-methylenebis(stearamidomethyl) thiocyanate are claimed to give a soft hand, superior fastness, and water repellency to various textile materials (24).

Many thiocyanates have been claimed to have insecticidal, fungicidal, bactericidal, and herbicidal properties. A few of these (Lethane 384, Lethane 60, and Thanite; see Table I) enjoy commercial use as insecticides today, particularly as toxicants in fly sprays (13,19,21,22). Nirit is a commercial agricultural fungicide which was developed in Germany (see *Insecticides*).

Like the isocyanates, the monoisothiocyanates have been cited in the patent literature as being useful for modifying plastics, and the polyisothiocyanates have been claimed for modifying resins to improve adhesion and for reacting with difunctional compounds to produce fibers. In these applications, however, the isocyanates have generally been the compounds of choice. (See *Phosgene* (*organic isocyanates*).) Allyl isothiocyanate has been reported in the patent literature to be effective as a pickling inhibitor in acid, as an antioxidant in lubricating oils, and as a preservative

in fruit juices, wines, and soy sauce. Various isothiocyanates have been stated to have bactericidal, fungicidal, and insecticidal properties. Phenyl, *o*-tolyl, *p*-methoxyphenyl, *m*-nitrobenzyl, and xenyl isothiocyanates have been suggested as reagents for amines.

Bibliography

(1) Beilstein, 4th ed.: Alkyl Thiocyanates, Vol. III, pp. 175–79.
(2) Brewster, R. Q., and Schroeder, W., "*p*-Thiocyanodimethylaniline," in Blatt, *Organic Syntheses*, Wiley, N.Y., 1943, Coll. Vol. II, p. 574.
(3) Brown, A. W. A., *Insect Control by Chemicals*, Wiley, N.Y., 1951.
(4) Challenger, F., and Collins, A. D., *J. Chem. Soc.*, **1924**, 1377.
(5) Dal Nogare, S., "Determination of Organic Sulfur Groups," in Mitchell, *Organic Analysis*, Interscience, N.Y.-London, 1953, Vol. I, pp. 393–97.
(6) Dains, F. B., Brewster, R. Q., and Olander, C. O., "Phenyl Isothiocyanate," in Blatt (see ref. 2), 1941, Coll. Vol. I, p. 447.
(7) Dyson, G. M., "*p*-Chlorophenyl Isothiocyanate," in Blatt (see ref. 2), Coll. Vol. I, p. 165.
(8) *J. Assoc. Offic. Agr. Chemists*, **36**, 97 (1953).
(9) Kaufman, H. P., *Angew. Chem.*, **54**, 195 (1941).
(10) Kharasch, N., Wehrmeister, H. L., and Tigerman, H., *J. Am. Chem. Soc.*, **69**, 1612 (1947).
(11) Mazzanti, L., and Lopez, M., *Boll. soc. ital. biol. sper.*, **26**, 1237 (1950); *C.A.*, **45**, 7242.
(12) Migrdichian, V., *The Chemistry of Organic Cyanogen Compounds*, Reinhold, N.Y., 1947.
(13) Murphy, D. F., and Peet, C. H., *J. Econ. Entomol.*, **25**, 123 (1932).
(14) Schriner, R. L., "Isopropyl Isothiocyanate," in Blatt (see ref. 2), Coll. Vol. II, p. 366.
(15) Schwartz, L., *U.S. Pub. Health Repts.*, **54**, 1426 (1939).
(16) Spoerri, P. E., and DuBois, A. S., "The Hoesch Synthesis," in Adams, *Organic Reactions*, Wiley, N.Y., 1949, Vol. V, p. 398.
(17) Walden, P., and Audrieth, L. F., *Chem. Revs.*, **5**, 339 (1928).
(18) Wood, J. L., "Substitution and Addition Reactions of Thiocyanogen," in Adams (see ref. 16), 1946, Vol. III, pp. 240–66.
(19) U.S. Pat. 1,808,893 (June 9, 1931), L. C. Heckert (to Rohm and Haas Co.).
(20) U.S. Pat. 2,203,649 (June 4, 1940), P. F. Felkers (to N. V. Stikstofbindingsindustrie "Nederland").
(21) U.S Pats. 2,217,611–2,217,615 (Oct. 8, 1940), J. N. Borglin (to Hercules Powder Co.).
(22) U.S. Pat. 2,220,521 (Nov. 5, 1940), W. F. Hester (to Rohm and Haas Co.).
(23) U.S. Pat. 2,310,670 (February 9, 1943), D. E. Badertscher, G. S. Crandall, and F. M. Seger (to Socony-Vacuum Oil Co.).
(24) U.S. Pat. 2,331,276 (Oct. 5, 1943), J. Pikl (to Du Pont).
(25) U.S. Pat. 2,404,727 (July 23, 1946), R. C. Houtz (to Du Pont).

W E Craig and J. O. Van Hook

THIOCYANIC ACID, HSCN. See *Cyanides (thiocyanates)*, Vol. **4**, p. 737.

THIOCYANOGEN, $(SCN)_2$. See *Cyanides (survey)*, Vol. **4**, p. 681.

THIOCYANOGEN VALUE. See *Fats and fatty oils*, Vol. **6**, p. 156; *Fatty acids (survey)*, Vol. **6**, p. 229.

THIODIETHYLENE GLYCOL, THIODIGLYCOL, $S(CH_2CH_2OH)_2$. See *Glycols*, Vol. **7**, p. 251.

THIOETHERS, RSR. See *Sulfides, organic*.

THIOGLYCOLIC ACID

Thioglycolic acid (thioglycollic acid, more systematically called mercaptoacetic acid or mercaptoethanoic acid), $HSCH_2COOH$, formula weight 92.11, is the sulfur analog of glycolic acid (*q.v.*) and is the simplest member of the group of mercapto carboxylic acids. It is a colorless liquid, possessing a faint sulfurous odor. It was identified in 1862 by Carius, who prepared it by reacting potassium hydrosulfide with potassium chloroacetate. Its primary use is in the form of its salts as a component of hair-waving and depilating compositions.

Properties

Constants. Pure thioglycolic acid has the following physical properties: m.p., 16.5°C.; b_{29}, 123°C.; b_6, 90°C.; d_4^{20}, 1.3253; heat of combustion, 346.3 kg.-cal./mole. The acid is miscible with water, methanol, ethyl alcohol, acetone, ether, chloroform, and benzene, but it is practically insoluble in petroleum ether.

Both the carboxyl group and the mercapto (sulfhydryl) group of thioglycolic acid possess acidic properties. The dissociation constants at 25°C. are 2.14×10^{-4} and 2.1×10^{-11}, respectively.

The e.m.f. of the system thioglycolic acid – dithiodiglycolic acid (see p. 82) in 0.1 *N* HCl is 0.233 v. (13). Polarographically, thioglycolic acid yields two waves having half-wave potentials of 0.295 and −0.025 v. at pH 0. The potentials vary with pH (16).

Reactions. Thioglycolic acid undergoes the reactions typical of both carboxylic acids and mercaptans (*q.v.*), forming salts, esters, amides, etc. (see "Derivatives"). It is also subject to self-esterification, leading to *S*-thioglycoloylthioglycolic acid, $HSCH_2COSCH_2COOH$, 1,4-dithioglycolide, $S.CH_2.CO.S.CH_2.CO$, and polythioglycolides of the linear, $HS[CH_2COS]_xCH_2COOH$, and cyclic, $[CH_2COS]_x$, types. The dehydration reaction proceeds less readily in the case of thioglycolic acid than in the case of glycolic acid and occurs extensively only if a dry inert gas is passed through the acid heated to 120°C. (18). However, self-esterification takes place to some extent even at room temperature when 75% or more concentrated acid is stored in a closed vessel. The relative concentration of free acid to polymers appears to be a function of the total acid concentration in the solution (see Table I (14)). Although the self-esterification can be reversed readily in the presence of dilute acids or alkalies,

TABLE I. Loss of Thioglycolic Acid Through Self-Esterification in Aqueous Solutions at Room Temperature.

Original concentration		Final concentration, M.e./g.	Change, %	Time of storage, days
%	M.e./g.			
97.15	10.56	9.50	10.04	283
94.58	10.28	9.31	9.44	346
91.08	9.90	9.26	6.46	283
86.20	9.37	8.96	4.37	283
84.18	9.15	8.96	2.08	346
82.16	8.93	8.62	3.47	283
73.69	8.01	7.92	1.13	346

thioglycolic acid is marketed as a 70% aqueous solution rather than the more concentrated product obtainable by vacuum distillation.

One of the more important and most widely used reactions of thioglycolic acid is that with disulfides, particularly cystine, in proteins such as wool and hair (7). It reacts reversibly with cystine, especially at elevated pH's, the equilibrium constant being of the order of magnitude of 1 (2):

$$\underset{\text{thioglycolic acid}}{2\,HSCH_2COOH} + \underset{\text{cystine}}{HOOCCH(NH_2)CH_2SSCH_2CH(NH_2)COOH} \rightleftharpoons$$
$$\underset{\text{cysteine}}{2\,HOOCCH(NH_2)CH_2SH} + \underset{\text{dithioglycolic acid}}{HOOCCH_2SSCH_2COOH}$$

The rate at which equilibrium is established is a function of pH: slow at pH's below 6 and rapid at pH's between 8 and 10.

Thioglycolic acid and especially its alkaline aqueous solutions are rapidly oxidized by air to the disulfide, dithiodiglycolic acid, or salts thereof in the presence of small amounts of copper, manganese, or iron (19). Mild chemical oxidation (for example, iodine) also leads to dithiodiglycolic acid, whereas more vigorous oxidative conditions (for example, dilute nitric acid) produce sulfoacetic acid, HO_3SCH_2COOH.

Thioglycolic acid readily forms mercaptals (*q.v.*) and mercaptoles with aldehydes or ketones.

Upon treatment with thiocyanic acid, thioglycolic acid is transformed into rhodanine, $\underline{CH_2.CO.NH.CS.S}$. With acetyl chloride thioglycolic acid yields *S*-acetylthioglycolic acid, CH_3COSCH_2COOH, b_{17} 158–59°C. In dilute alkali, thioglycolic acid reacts with alkylene dihalides to yield the corresponding *S,S*-alkylenebisthioglycolic acids.

Toxicity. Thioglycolic acid is a stronger acid than acetic acid and produces irritation if it comes in contact with abrasions and sores of the skin. Although short contact of the acid or of its solutions with unbroken areas of the skin is generally not harmful, such contact should be avoided by wearing protective rubber clothing and safety goggles.

Neutral or slightly alkaline solutions of thioglycolates are less irritating than solutions of the free acid. The mildness of alkaline thioglycolate solutions is indicated by the fact that cold-wave lotions are widely used without deleterious effects (5,8) and are considered safe for general use (1).

Animal studies indicate that thioglycolic acid taken internally is toxic in dosages larger than approximately 0.15 g./kg. (11).

Preparation

Thioglycolic acid is prepared commercially by the reaction of sodium chloroacetate with sodium hydrosulfide in an aqueous medium. Thiodiglycolic acid, dithiodiglycolic acid, and glycolic acid are the principal side products. After acidification, thioglycolic acid is extracted from the reaction mixture into ethyl ether or other suitable organic solvents and purified by vacuum distillation.

An alternate method of manufacture involves the hydrolysis with dilute sulfuric acid of an alkali salt of thiosulfatoacetic acid, HO_3SSCH_2COOH (a Bunte salt; see pp. 110,113), formed by the reaction of an alkali chloroacetate with an alkali thiosulfate (23a). The hydrolysis mixture is then reduced with zinc to yield thioglycolic

acid, which may be extracted with a solvent. It has been suggested (4) that thioglycolic acid can be prepared conveniently by hydrolysis of the guanidonium salt:

$$ClCH_2COONa + HN_2CSNH_2 \longrightarrow \begin{matrix} NH_2 \\ NH_2 \end{matrix}\!\!\gg\!CSCH_2COOH + NaCl$$

$$\begin{matrix} NH \\ NH_2 \end{matrix}\!\!\gg\!CSCH_2COOH + NH_3 \longrightarrow [NH_2C(=NH_2)NH_2]^+[HSCH_2COO]^-$$

Thioglycolic acid can be prepared by treating chloroacetic acid with an alkali polysulfide and reducing the resulting dithiodiglycolic acid with zinc dust (24). A solution of glycolic acid will react with hydrogen sulfide in the presence of silver oxide to yield thioglycolic acid, thiodiglycolic acids, and other products.

Market Forms and Standards

Thioglycolic acid is offered today primarily as the 70% aqueous solution. It is obtainable also as the 95–100% acid. The ammonium salt is available in the form of a 55–65% aqueous solution.

Seventy per cent thioglycolic acid or the solution of the ammonium salt is generally shipped in 13-gal. glass carboys. The ammonium salt is also frequently shipped in 55-gal. aluminum drums. A warning label is usually affixed: "Warning! May Cause Burns. Avoid Contact With Skin, Eyes, and Clothing."

Standards for cosmetic-grade thioglycolic acid and ammonium thioglycolate are listed in Table II (3).

TABLE II. Standards for Cosmetic-Grade Thioglycolic Acid and Ammonium Thioglycolate.

Property	Thioglycolic acid	Ammonium thioglycolate
Solubility	Miscible with acetone, ethyl alcohol, ether, and water	Miscible with ethyl alcohol and water; immiscible with acetone, benzene, chloroform, and ether
Color	Colorless to light yellow	—
Ash	0.05% max.	0.05% max.
Thioglycolic acid	65–75%	45–55% as thioglycolic acid
Dithiodiglycolic acid	2% max.	2% max.
Iron, copper, lead, arsenic	1 p.p.m. max. each	1 p.p.m. max. each
Turbidity	A 10% aqueous solution (based on thioglycolic acid) must not show any turbidity	—
Odor	Acceptable	Acceptable

Analysis

Identification. Thioglycolic acid forms a violet-purple color with sodium nitroprusside, $Na_2[Fe(CN)_5NO].2H_2O$, in dilute ammoniacal solution. A neutral solution of the acid yields a transient blue color with ferric ion, whereas an ammoniacal solution produces a deep red-violet color with ferric iron. With cadmium ion in dilute acetic acid solution, thioglycolic acid forms a white gelatinous precipitate soluble in ammonium hydroxide. With nitrous acid, thioglycolic acid yields a colored nitrosyl mercaptide (15,21). These reactions are not specific for thioglycolic acid but rather

are typical for most mercaptans. The simplest derivative for identification of thioglycolic acid is dithiodiglycolic acid (see p. 82), melting at 108–9°C.

Determination. In the absence of other reducing agents or interfering substances, thioglycolic acid may be determined directly by titration with standard iodine after acidification with hydrochloric acid (11). The total acidity of solutions of thioglycolic acid is determined by titration with standard alkali to pH 6.7–7.0. The acid is generally considered pure if the concentration determined iodometrically is equal to that determined acidimetrically.

Uses

Salts of thioglycolic acid are used successfully for the cold-waving of human hair. The active ingredient of most modern hair-waving lotions is 5–9% ammonium thioglycolate (3a,28) adjusted to a pH between 8.6 and 9.6 with ammonium carbonate or hydroxide. Primarily, the cold-waving lotion appears to reduce part of the cystine (S—S) groups present in hair to cysteine type (SH) linkages. This reaction is then followed by a series of complex physical and chemical changes (23) during which the desired curl is "fixed" in the hair. Re-formation of cystine linkages in hair and removal of excess thioglycolic acid is accomplished generally through chemical oxidation by hydrogen peroxide, perborate, or bromate (27) or simply through air oxidation in the presence or absence of a catalyst (26). See also *Shampoos*, Vol. **12**, p. 239.

Salts of thioglycolates, especially those of nonvolatile alkalies, adjusted to pH's between 10 and 11 are used extensively as depilating agents (20). Calcium thioglycolate is widely used for this purpose. Thioglycolates have been used for some time for the dehairing of hides (25).

The physical and chemical properties of wool (*q.v.*) may be altered by reduction of cystine groups in wool by alkaline thioglycolates, followed by alkylation of the cysteine formed with alkylene dihalides. Wool treated in this manner shows greater resistance to the action of alkalies, acids, and oxidizing and reducing agents and is attacked less readily by moths and carpet beetles (6). See also "Mothproofing of wool" under *Textile technology*, Vol. **13**, p. 903.

It has been suggested recently that thioglycolic acid converts rubbery hydrocarbons to derivatives possessing resistance to the solvating action of liquid hydrocarbon solvents (29).

The color reaction between thioglycolates and iron salts is the basis of a sensitive qualitative test for iron. This reaction has also been adopted for the quantitative determination of iron.

Derivatives

Derivatives of thioglycolic acid may be formed by reactions involving the mercaptan group or the carboxyl group of the molecule or both.

BY MODIFICATION OF THE MERCAPTAN GROUP

Simple Thioethers (21). Simple thioethers are generally formed by treatment of a sodium mercaptide, RSNa, with sodium chloroacetate. The physical constants of some of these ethers have been studied thoroughly (see Table III) (12).

Thiodiglycolic Acid. Thiodiglycolic acid (thiodiglycollic acid, thiodiacetic acid, thiodiethanoic acid), $HOOCCH_2SCH_2COOH$, formula weight 150.15, is a white solid,

TABLE III. Physical Properties of Thioethers of Thioglycolic Acid.

Thio ether	B.p., °C.	M.p., °C.	d_{20}^{25}	n_D^{20}	K × 10⁴
Methyl	$130–131_{27}$	—	1.233	1.495	1.92
Ethyl	$117–118_{11}$	—	1.518	—	1.83
n-Propyl	132_{15}	—	1.109	1.483	1.68
Isopropyl	128_{13}	—	—	—	1.9
n-Butyl	$140–144_{10–15}$	—	1.0631_{25}^{25}	1.4780^{25}	1.54
Phenyl	—	60	—	—	3.00
Benzyl	—	64	—	—	1.87
Triphenylmethyl	—	162	—	—	0.48

m.p. 129°C. Its ionization constants are reported as $K_1 = 4.9 \times 10^{-4}$ and $K_2 = 3.5 \times 10^{-5}$. Thiodiglycolic acid is formed, together with some thioglycolic acid and dithiodiglycolic acid, in the reaction between sodium sulfide and sodium chloroacetate (see p. 79).

Dithiodiglycolic Acid. Dithiodiglycolic acid (dithiodiglycollic acid, dithiodiacetic acid, dithiodiethanoic acid), $HOOCCH_2SSCH_2COOH$, formula weight 182.22, is a white solid, m.p. 108–109°C. Its ionization constants are reported as $K_1 = 6.5 \times 10^{-4}$ and $K_2 = 5.2 \times 10^{-5}$.

As a disulfide, dithiodiglycolic acid can be reduced to the mercaptan, thioglycolic acid, with zinc amalgam, tin and acid, sodium amalgam, or electrolytically. Dithiodiglycolic acid undergoes other typical reactions of a disulfide (see Vol. **13**, p. 300), forming a sulfenate and thioglycolate with alkalies (17), a thiocyano derivative and thioglycolate with cyanides, and a thiosulfate (Bunte salt) and thioglycolate with sulfites or bisulfites (19):

$$(OOCCH_2SSCH_2COO)^{2-} + 2OH^- \rightleftharpoons (OOCCH_2SO)^{2-} + (OOCCH_2S)^{2-} + H_2O$$

$$(OOCCH_2SSCH_2COO)^{2-} + CN^- \rightleftharpoons (OOCCH_2SCN)^- + (OOCCH_2S)^{2-}$$

$$(OOCCH_2SSCH_2COO)^{2-} + SO_3^{2-} \rightleftharpoons (OOCCH_2SSO_3)^{2-} + (OOCCH_2S)^{2-}$$

The reaction with sulfites has been utilized in the preparations of cold-waving lotions (31). Ammonium dithiodiglycolate has also been used in thioglycolate waving lotions.

Dithiodiglycolic acid is prepared by mild oxidation of thioglycolic acid or by reaction of sodium disulfide with sodium chloroacetate.

BY MODIFICATION OF THE CARBOXYL GROUP

Salts *Ammonium thioglycolate*, NH_4OOCCH_2SH, formula weight 109.15, may be obtained in prismatic crystals by passing dry ammonia into an ether solution of thioglycolic acid. It is available commercially as a 55–65% aqueous solution and is used for the preparation of cold-wave lotions.

Sodium thioglycolate, $NaOOCCH_2SH$, formula weight 114.10, has been available commercially as a 40–45% aqueous solution and as a dry white powder for use in cold-wave lotions and depilatories.

Esters. With the exception of ethyl thioglycolate, the simple esters of thioglycolic acid have not been described extensively. *Ethyl thioglycolate*, $HSCH_2COOC_2H_5$, b, 156–158°C.; b_{17}, 55°C.; d_{15}^{15}, 1.0964, is an unpleasant smelling material that may be prepared from thioglycolic acid and ethyl alcohol in the presence of sulfuric acid.

Isooctyl thioglycolate, b_{17}, 125°C.; d^{25}, 0.9736, is available commercially for use as a plasticizer.

It has been suggested recently that addition of ethyl thioglycolate or higher-molecular-weight esters of thioglycolic acid to polysiloxane lubricating fluids (see *Silicones*, Vol. **12**, p. 401) will assist in increasing their load-carrying properties (30).

Amides. The substituted amides are generally prepared by reacting the amine with chloroacetic acid and ammonium thiocyanate. The product of this reaction is then hydrolyzed to the desired amide (22). The amides of thioglycolic acid may also be prepared by treatment of the ethyl ester with ammonia or an amine.

Thioglycolic acid anilide (2-mercaptoacetanilide), $HSCH_2CONHC_6H_5$, formula weight 167.21, m.p. 110.5–11°C., is a sensitive reagent for the detection of cobalt (22).

Thionalide (2-mercapto-*N*-2-naphthylacetamide, "thioglycolic-β-aminonaphthalide"), $HSCH_2CONHC_{10}H_7$, formula weight 217.28, m.p. 109–9.5°C., is used for the determination of arsenic, antimony, bismuth, calcium, copper, lead, mercury, rhodium, ruthenium, silver, and thallium (22).

Bibliography

(1) Behrman, H. T., *et al.*, *J. Am. Med. Assoc.*, **140**, 1208–9 (1949).
(2) Bersin, T., and Steudel, I., *Ber.*, **B71**, 1015–25 (1938).
(3) Board of Standards, The Toilet Goods Assoc., Inc., *Toilet Goods Assoc., Spec.*, No. **31** (April 27 1949); No. **32** (May 20, 1949).
(3a) Cifelli, T., *Drug & Cosmetic Ind.*, **74**, 263–65, 290–92 (1954).
(4) Curphey, E. G., *Chemistry and Industry*, **1951**, 840–41.
(5) Draize, J. H., *et al.*, *Proc. Sci. Sect. Toilet Goods Assoc.*, **7**, 29–31 (1947).
(6) Geiger, W., *et al.*, *Ind. Eng. Chem.*, **34**, 1398–1402 (1942).
(7) Goddard, D., and Michaelis, L., *J. Biol. Chem.*, **106**, 605–14 (1934).
(8) Goldman, L., *et al.*, *J. Am. Med. Assoc.*, **137**, 354–57 (1948).
(9) Hill, R., and Lewis, H., *J. Biol. Chem.*, **59**, 557–67 (1924).
(10) Kharasch, M., *et al.*, *J. Biol. Chem.*, **113**, 537–55 (1936).
(11) Kramer, H., *J. Assoc. Offic. Agr. Chemists*, **35**, 285–87 (1952).
(12) Larsson, E., *Ber.*, **B63**, 1347–52 (1930).
(13) Larsson, E., *Svensk Kem. Tidsk.*, **45**, 65–72 (1933); *C.A.* **27**, 3384.
(14) Mulvaney, J. F., *Proc. Sci. Sect. Toilet Goods Assoc.*, **5**, 133–38 (1946).
(15) Ruemle, T., and Walker, G., *Soap, Perfumery & Cosmetics*, **26**, 461–62 (1953).
(16) Sartori, G., *et al.*, *Comité intern. thermodynam. et cinét. électrochim., Compt. rend. réunion*, **1950**, 301–4; *C.A.*, **46**, 10011.
(17) Schoberl, A., and Eck, H., *Ann.*, **522**, 97–115 (1936).
(18) Schoberl, A., and Krumey, F., *Ber.*, **B77**, 371–77 (1944).
(19) Stricks, W., and Kolthoff, M., *J. Am. Chem. Soc.*, **73**, 4569–74 (1951).
(20) Van Sluis, H., *Perfumery Essent. Oil Record*, **40**, 323, 337 (1949).
(21) Walker, G., *Soap, Perfumery & Cosmetics*, **26**, 1238–40 (1953); **27**, 75–77 (1954).
(22) Welcher, F. J., *Organic Analytical Reagents*, Van Nostrand, N.Y., 1948, Vol. IV, pp. 163–64, 165–77.
(23) Whitman, R., *Proc. Sci. Sect. Toilet Goods Assoc.*, **18**, 27–32 (1952).
(23a) Fr. Pat. 929,112 (Jan. 24, 1946), G. Carpéni and P. Souchai.
(24) Ger. Pat. 180,875 (Oct. 27, 1905), Kalle & Co.
(25) U.S. Pat. 1,973,130 (Sept. 11, 1934), H. Turley and W. Windus (to Rohm and Haas).
(26) U.S. Pat. 2,540,980 (Feb. 6, 1951), M. Den Beste and R. Reed (to Raymond Labs.).
(27) U.S. Pat. 2,564,722 (Aug. 21, 1951), R. Reed *et al.* (to Raymond Labs.).
(28) U.S. Pat. 2,577,710 (Dec. 4, 1951), E. G. McDonough (to Procter and Gamble).
(29) U.S. Pat. 2,589,151 (March 11, 1952), G. E. Sernink (to Standard Oil Development).
(30) U.S. Pat. 2,597,045 (May 20, 1952), D. Willock and M. Sprung (to General Electric).
(31) U.S. Pat. 2,615,828 (Oct. 28, 1952), J. W. Hachele (to Procter and Gamble).

S. D. Gershon and M. M. Rieger

THIOINDIGO, $S.C_6H_4.CO.C{:}C.CO.C_6H_4.S$; **THIOINDIGOID DYES.** See *Indigoid dyes*, Vol. **7,** p. 823; *Pigments (organic)*, Vol. **10,** p. 673.

THIOKETONES, R_2CS. See *Sulfur compounds, organic,* Vol. **13,** p. 442.

THIOLS, RSH. See *Mercaptans.*

THIOLSULFONATES, RSO_2SR. See *Sulfur compounds, organic,* Vol. **13,** p. 443.

THIONALIDE, $HSCH_2CONHC_{10}H_7$. See *Thioglycolic acid.*

THIONATION. See *Sulfur dyes,* Vol. **13,** p. 450.

THIONES, R_2CS. See *Sulfur compounds, organic,* Vol. **13,** p. 442.

THIONIC ACIDS

Thionic acids have the composition $H_2S_nO_6$; in *polythionic acids,* as the term is usually understood, $n>2$. The anions $S_nO_6^{2-}$ with $n = 2$–6 are stable and well known; anions with a higher content of sulfur with n up to 10 have also been described (73,86).

Monothionic acid, HSO_3, is the first unstable oxidation product of hydrogen sulfite, HSO_3^-. Monothionic acid polymerizes rapidly to form dithionic acid, $H_2S_2O_6$. Monothionic and dithionic acids are not classed with the polythionic acids, because $H_2S_2O_6$ has no direct genetic relation to the acids containing greater proportions of sulfur ($H_2S_3O_6$, trithionic acid; $H_2S_4O_6$, tetrathionic acid; $H_2S_5O_6$, pentathionic acid; and $H_2S_6O_6$, hexathionic acid) and differs greatly from them in chemical properties. The true polythionic acids can be formed by reduction of sulfurous acid, are all easily convertible into one another, and are very similar in their properties. The dithionate ion, in contrast to polythionate ions, is stable in alkaline solution, while it decomposes into sulfurous and sulfuric acids in acid solution.

Dithionic acid was first prepared by Gay-Lussac and Welter in 1819. Even earlier, in 1812, the first indication of the existence of the polythionic acids was found by Dalton in the action of hydrogen sulfide on aqueous solutions of sulfurous acid. In this solution—*Wackenroder's liquid*—Wackenroder in 1846 found the acid $H_2S_5O_6$ and Debus in 1888 found the acid $H_2S_6O_6$, along with $H_2S_3O_6$ (discovered by Langlois in 1840), and $H_2S_4O_6$ (found first by Fordos and Gélis in 1842). The chemistry of the thionic acids was examined later mainly by Bassett, Foerster, Foss, Goehring, Hansen, Kurtenacker, Riesenfeld, Stamm, and their students.

Polythionic acids are found in nature in minor quantities in the water of certain lakes and springs from sulfur-containing volcanoes (16b). Polythionates are also formed in the soil during the oxidation of elemental sulfur by bacteria (46). The use of polythionates as agricultural fungicides and for dermatological and cosmetic applications has been suggested.

Dithionic Acid

PHYSICAL AND CHEMICAL PROPERTIES

Anhydrous dithionic acid, $H_2S_2O_6$, is not known. The aqueous solution can be concentrated to a specific gravity of 1.35 at room temperature; more concentrated solutions decompose rapidly into sulfur dioxide and sulfuric acid even at room temperature. Dithionic acid in aqueous solution is a strong dibasic acid. Dithionates of the alkali and alkaline earth metals are stable in the anhydrous state at room temperature; at higher temperatures they decompose into sulfur dioxide and metal sulfates. Other

metal dithionates are more or less stable, depending on the metals (9). Aqueous solutions of the metal dithionates can be refluxed for hours without decomposition.

From x-ray studies and general physical and chemical data, the structure of the dithionate ion has been shown to be $[O_3S—SO_3]^{2-}$, with an S—S bond distance of 2.08 A. and S—O distance of 1.50 A. (1,91).

Aqueous solutions of dithionic acid decompose according to the equation:

$$H_2S_2O_6 \longrightarrow H_2SO_4 + SO_2 \qquad (1)$$

The decomposition is speeded up by hydrogen ions (4,10), as well as by heavy water (7), alcohols, glycerol, or acetone (8), and by raising the temperature; it is slowed down by addition of neutral salts (6). Oxidizing agents react with dithionic acid only when the conditions are suitable for decomposition; therefore, they must react with the sulfurous acid formed. Likewise, reducing agents like "nascent" hydrogen react with dithionic acid only insofar as decomposition, that is, formation of sulfur dioxide, takes place.

PREPARATION

Dithionic acid and its salts are obtained by oxidizing sulfurous acid or hydrogen sulfites with oxidizing agents that do not react too fast with HSO_3^-, or by electrolytic oxidation. Especially suitable oxidizing agents are manganese dioxide (5) or permanganate in a weak acid medium, cobaltic hydroxide, and peroxymonosulfuric acid, H_2SO_5. The radical monothionic acid, HSO_3 (3), is formed first. The proportions of dithionate and sulfate formed with various oxidizing agents have been studied (2).

Polythionic Acids

PHYSICAL AND CHEMICAL PROPERTIES

Polythionic acids are not known in the anhydrous form, but exist only in aqueous solutions that can be concentrated to a sirupy consistency. These solutions are unstable and decompose more or less rapidly depending on the pH of the solution. The solutions become more unstable as the temperature and concentration are increased. All polythionic acids are contained in a Wackenroder liquid that can be concentrated in a vacuum to a specific gravity of 1.6, that is, to a content of about 60% polythionic acid (mainly pentathionic acid). The polythionic acids are stronger than sulfuric acid (58,59). They are the dispersing and stabilizing parts of true hydrophilic sulfur sols (88).

Among the salts, normal alkali, ammonium, and alkaline earth polythionates have been prepared (31,40,65,73,79,84,89); normal iron(II) and zinc polythionates (17,18) are also known. No acid salts are known. All the salts are easily soluble in water. The alkali salts are insoluble in alcohol, whereas some of the heavy-metal salts are soluble in alcohol. The solutions are neutral, and, if pure, are relatively stable.

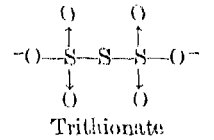
Esters of trithionic and tetrathionic acids have been prepared by Foss (31,34).

Structure and Physical Constants. Blomstrand and Mendeleev in 1870 proposed formulas with unbranched sulfur chains for polythionate ions; these also give the best agreement with the K_α spectrum of sulfur in these compounds (20). Structure determinations by means of x-rays were made on $K_2S_3O_6$ (91), $Na_2S_4O_6.2H_2O$, $(NH_4)_2S_4O_6$, $Rb_2S_4O_6$ (35), $BaS_4O_6.2H_2O$ (36), $Rb_2S_5O_6$, $Cs_2S_5O_6$, and $BaS_5O_6.2H_2O$ (37). According to the structural investigations of Zachariasen on $K_2S_3O_6$, the $S_3O_6^{2-}$ ion exists in the form of a zigzag formed by three sulfur atoms. Two of the sulfur atoms

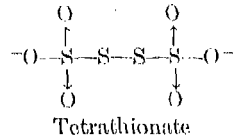
of $S_3O_6^{2-}$ are each tetrahedrally surrounded by 3 O and 1 S, the two tetrahedra having in common the corner occupied by the S atom; the angle at the center sulfur is 103°, and the distances are S—S 2.15 A. and S—O 1.50 A. In $S_4O_6^{2-}$ and $S_5O_6^{2-}$, according to Foss, unbranched sulfur chains are also present. In the pentathionate the configuration of the sulfur chain is analogous to the positions of 5 sulfur atoms in the orthorhombic S_8 ring of sulfur (87). Foss found the angle at the middle sulfur atom S(3) to be 106° and at the two adjacent S atoms 103°. The distance S—O in S_5O_6 was found to be 1.43 A., the distance between the two adjacent sulfur atoms S(1)—S(2) 2.14 A., and the distance S(2)—S(3) 2.05 A.

Polythionate ions have a characteristic Raman spectrum (19). The x-ray emission spectrum of the sulfur in the polythionates contains a K_α doublet, indicating that there are sulfur atoms of different oxidation states, that is, sulfur of about the same electronegativity as in sulfate in addition to sulfur of about the same electronegativity of elementary sulfur.

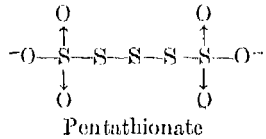
Chemical and physical studies (16a,37a,37b) indicate structures containing sulfite and thiosulfate groups attached to sulfur:



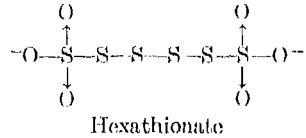
Trithionate



Tetrathionate



Pentathionate



Hexathionate

The electric conductivity of tetrathionic acid at 25°C. is λ_∞ = 843 mhos, according to Ostwald, and 864.2 mhos according to Hertlein. The velocity of migration of the anions is: $\frac{1}{2}S_3O_6^{2-}$ = 77.5, $\frac{1}{2}S_4O_6^{2-}$ = 71.7, and $\frac{1}{2}S_5O_6^{2-}$ = 65.3. The heats of formation from the elements are 270.1 kg.-cal. for $H_2S_3O_6$.aq., 260.8 kg.-cal. for $H_2S_4O_6$.aq., and 251.5 kg.-cal. for $H_2S_5O_6$ (11).

REACTIONS

Decomposition of Polythionates in Aqueous Solution. Polythionate ions in aqueous solution are stable for only a short time; they undergo spontaneous decomposition, finally forming sulfite, sulfate, and thiosulfate, and, in the case of higher polythionates, also sulfur. The apparently unpredictable behavior of the polythionates on hydrolysis becomes at least in part understandable if it is considered that the reactions of formation (eqs. 29–32) (see p. 89) are reversible under the influence of nucleophilic reagents (32,45,53).

Trithionate decomposes slowly in acid and weakly alkaline solution according to equation (2). Potassium trithionate (0.1 *M*) decomposes 55% within 28 days at room temperature. This reaction is to a large extent independent of the pH of the solution. At 40°C. and at a pH of 0.5–13, a 0.13 *M* solution of potassium trithionate decomposes 50% within 27 hr., and at 50°C. within 24 hr. (42,74). At higher concentrations of alkali (pH > 13) reaction (3) takes place (71).

$$S_3O_6^{2-} + H_2O \longrightarrow S_2O_3^{2-} + SO_4^{2-} + 2\,H^+ \qquad (2)$$

$$2\,S_3O_6^{2-} + 6\,OH^- \longrightarrow S_2O_3^{2-} + 4\,SO_3^{2-} + 3\,H_2O \qquad (3)$$

Polythionates with more than three sulfur atoms per molecule are more stable to acids, but less stable to alkali solutions, than trithionate. In acid solution tetrathionate and a mixture of tetrathionate and pentathionate can be stabilized by the addition of traces of cupric salts (120). The cupric salts presumably prevent the formation of catalytic thiosulfate and sulfite (eqs. 12, 13).

Tetrathionate at pH 8.9 and 50°C. decomposes according to equation (4) (69,74); at pH 11.5 (0.5 *N* ammonia solution) or in a 0.5 *N* solution of sodium carbonate reaction (5) takes place (49,71); and on longer treatment with alkali solution reaction (6):

$$2\,S_4O_6^{2-} \longrightarrow S_3O_6^{2-} + S_5O_6^{2-} \tag{4}$$

$$4\,S_4O_6^{2-} + 6\,OH^- \longrightarrow 2\,S_3O_6^{2-} + 5\,S_2O_3^{2-} + 3\,H_2O \tag{5}$$

$$2\,S_4O_6^{2-} + 6\,OH^- \longrightarrow 3\,S_2O_3^{2-} + 2\,SO_3^{2-} + 3\,H_2O \tag{6}$$

If piperidine is used as the nucleophilic reagent, 1,1′-thiodipiperidine is formed (eq. 7):

$$S_4O_6^{2-} + 4\,C_5H_{10}NH \longrightarrow S(NC_5H_{10})_2 + 2\,C_5H_{10}NH_2^+ + SO_3^{2-} + S_2O_3^{2-} \tag{7}$$

In the presence of OH^- as nucleophilic reagent, different reaction mechanisms are possible depending on the pH (42). In less strongly alkaline solution a decomposition of the tetrathionate ion by sulfite takes place (eq. 12) instead of the above reactions, leading to the formation of trithionate and thiosulfate. With decreasing OH^- concentration, pentathionate can be formed from tetrathionate in addition to the above reaction products, because reaction (4) can take place instead of the decomposition according to equation (6). Reaction (4) takes place whenever the thiosulfate ion is present since it is catalyzed by this ion. This thiosulfate catalysis causes the decomposition of even neutral tetrathionate solutions in a few hours, whereas neutral tetrathionate solutions, if pure, can be kept for weeks at room temperature.

Pentathionate and *hexathionate* in neutral solutions decompose according to equations (8) and (9), which are catalyzed by thiosulfate ion (25,49):

$$S_5O_6^{2-} \longrightarrow S_4O_6^{2-} + S \tag{8}$$

$$S_6O_6^{2-} \longrightarrow S_5O_6^{2-} + S \tag{9}$$

Pentathionate and hexathionate are very sensitive to alkali (49), decomposing like the tetrathionate according to equations (10) and (11):

$$2\,S_5O_6^{2-} + 6\,OH^- \longrightarrow 5\,S_2O_3^{2-} + 3\,H_2O \tag{10}$$

$$2\,S_6O_6^{2-} + 6\,OH^- \longrightarrow 5\,S_2O_3^{2-} + 2\,S + 3\,H_2O \tag{11}$$

With piperidine as nucleophilic reagent, thiodipiperidine (or dithiodipiperidine in the case of hexathionate) is also formed (32,33,42). At medium pH values both types of decomposition take place, and subsequent hydrolysis of the polythionates formed according to equations (8) and (9) complicates the picture.

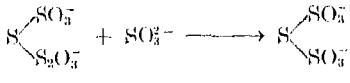
Reactions of Polythionates with Sulfite Ion, Hydrogen Sulfite Ion, and Thiosulfate Ion in Aqueous Solution. Trithionate ion reacts neither with sulfite nor with hydrogen sulfite. However, tetrathionate (61,67), pentathionate (23), and hexathionate (89) react:

$$S_4O_6^{2-} + SO_3^{2-} \rightleftharpoons S_3O_6^{2-} + S_2O_3^{2-} \tag{12}$$

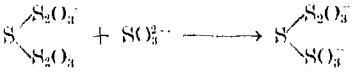
$$S_5O_6^{2-} + SO_3^{2-} \rightleftharpoons S_4O_6^{2-} + S_2O_3^{2-} \tag{13}$$

$$S_6O_6^{2-} + SO_3^{2-} \longrightarrow S_5O_6^{2-} + S_2O_3^{2-} \tag{14}$$

The equilibriums are on the right-hand side at high pH values, on the left-hand side at low pH values (85). The reactions are to be understood as an exchange of the ligand $S_2O_3^{2-}$ for SO_3^{2-} as shown in equations (15) and (16) (16,33).



(15)



(16)

Reactions of Polythionates with Cyanide Ion in Aqueous Solution. *Trithionate* reacts with cyanide ion on heating to form sulfite, hydrogen sulfate, and thiocyanate (33,79):

$$[O_3S{-}S{-}SO_3]^- + CN^- \longrightarrow [O_3S{-}S{-}CN]^- + SO_3^{2-} \quad (17)$$

$$[O_3S{-}S{-}CN]^- + OH^- \longrightarrow [O_3SOH]^- + SCN^- \quad (18)$$

Tetrathionate ion and *pentathionate* ion react similarly with cyanide ion to give first the ions $[O_3S{-}S{-}CN]^-$ and $[O_3S_2{-}S{-}CN]^{2-}$ respectively, and then thiosulfate, thiocyanate, and hydrogen sulfate (60,63,64,66). The reactions occur as follows, reaction (19) being followed by (18):

$$[O_3S{-}S{-}S_2O_3]^{2-} + CN^- \longrightarrow [O_3S{-}S{-}CN]^- + S_2O_3^{2-} \quad (19)$$

$$[O_3S_2{-}S{-}S_2O_3]^{2-} + CN^- \longrightarrow [O_3S_2{-}S{-}CN]^- + S_2O_3^{2-} \quad (20)$$

$$[O_3S_2{-}S{-}CN]^- + S_2O_3^{2-} \longrightarrow [O_3S{-}S{-}S_2O_3]^{2-} + SCN^- \quad (21)$$

Further reaction of the tetrathionate formed in reaction (21) leads to the overall reactions:

$$S_4O_6^{2-} + CN^- + OH^- \longrightarrow SCN^- + S_2O_3^{2-} + HSO_4^- \quad (22)$$

$$S_5O_6^{2-} + 2\,CN^- + OH^- \longrightarrow 2\,SCN^- + S_2O_3^{2-} + HSO_4^- \quad (23)$$

$$S_6O_6^{2-} + 3\,CN^- + OH^- \longrightarrow 3\,SCN^- + S_2O_3^{2-} + HSO_4^- \quad (24)$$

Reactions of Polythionates with Hydrogen Sulfide or Sulfide Ion in Aqueous Solution. The reaction of polythionate ions with **gaseous hydrogen sulfide** gives the following picture (21). Trithionate ion reacts with hydrogen sulfide exceedingly slowly and to an insignificant degree. Polythionate ion of higher sulfur content reacts in solution that is alkaline at the beginning of the reaction as follows:

$$S_nO_6^{2-} + H_2S + 2\,OH^- \longrightarrow 2\,S_2O_3^{2-} + (n-3)\,S + 2\,H_2O \quad (25)$$

In acid solution, on the other hand, higher polythionate reacts with more hydrogen sulfide (22,81): three moles of hydrogen sulfide per mole of polythionate:

$$S_nO_6^{2-} + 3\,H_2S \longrightarrow S_2O_3^{2-} + (n+1)\,S + 3\,H_2O \quad (26)$$

These reactions have been explained by assuming that the polythionate ions are first broken down into smaller charged ("polarized") portions (70). The reaction between polythionate and hydrogen sulfide in acid or neutral solution is complicated, however, by the formation of a considerable quantity of pentathionate according to reaction (27):

$$S_4O_6^{2-} + S \rightleftharpoons S_5O_6^{2-} \quad (27)$$

The equilibrium point of reaction (27) is dependent on the pH.

Reactions (25) and (26) are slow; an increase of the hydrogen-ion concentration

slows down the absorption of hydrogen sulfide by polythionate solutions. Pentathionate reacts somewhat more slowly than tetrathionate (70).

The reaction of polythionates with **sulfide ion** in alkaline solution proceeds by equation (28):

$$S_nO_6^{2-} + S^{2-} \longrightarrow 2\,S_2O_3^{2-} + (n-3)\,S \qquad (28)$$

Trithionate reacts in this manner but more slowly than other polythionates (51,67).

It has often been proposed to use polythionates as absorbents for hydrogen sulfide, but such processes have not been put into operation because the insufficient knowledge of the complex reaction mechanism would make exact control of the reaction impossible.

Reactions of Polythionates with Salts of Metals (62). *Trithionate* forms sulfides on heating with salts of heavy metals that give difficultly soluble sulfides. The reaction with mercury(I) nitrate is characteristic, forming black mercury sulfide with trithionate even in the cold. Similarly, the reaction with copper(II) salts forms copper sulfide on heating.

Tetrathionate and *pentathionate*, in contrast to trithionate, with mercury(I) nitrate give yellow precipitates that become black on heating.

Pentathionate and *hexathionate* in contrast to all other polythionates form a brown precipitate with an ammoniated solution of a silver salt and a black precipitate with ammoniated mercury(II) cyanide solution at high temperatures.

ANALYSIS OF SOLUTIONS OF POLYTHIONATES

Qualitative detection of polythionates is given by the precipitation with mercury(I) nitrate; thiosulfate ion interferes with this reaction. The presence of pentathionate is best shown by the reaction with an ammoniated solution of a silver salt or by the immediate precipitation of sulfur on the addition of sodium hydroxide solution. Hexathionate reacts like pentathionate in these reactions; it can be recognized by the fact that on addition of a dilute ammonia solution sulfur is precipitated within a few seconds, while with pentathionate the reaction occurs only after 5–10 minutes under those conditions.

There are several processes for *quantitative determination* (62) of polythionates. By far the most reliable process is the indirect analysis in which several samples of polythionate are exposed to the action of solutions of sulfite, cyanide, and sulfide. In the reactions thiosulfate is formed in different amounts and is titrated. If hexathionate is present, an additional reaction with sodium hydroxide solution can be used to determine it (49).

PREPARATION

Polythionic acids and their salts can, in the main, be produced by the following reactions.

Reaction of Sulfur Halides (as SCl_2 and S_2Cl_2) or of Other Derivatives of S^{II} or S_2^{II} with HSO_3^- and $S_2O_3^{2-}$. The methods of preparation are based on the following fundamental equations:

$$SX_2 + 2\,HSO_3^- \longrightarrow S_3O_6^{2-} + 2\,HX \qquad (29)$$

$$S_2X_2 + 2\,HSO_3^- \longrightarrow S_4O_6^{2-} + 2\,HX \qquad (30)$$

$$SX_2 + 2\,S_2O_3^{2-} \longrightarrow S_5O_6^{2-} + 2\,X^- \qquad (31)$$

$$S_2X_2 + 2\,S_2O_3^{2-} \longrightarrow S_6O_6^{2-} + 2\,X^- \qquad (32)$$

According to equation (29) a method was worked out for *potassium trithionate* (84) in which sulfur dichloride is dissolved in an inert organic solvent, for example carbon tetrachloride, and treated below +10°C. with a concentrated solution of potassium hydrogen sulfite. *Potassium pentathionate* is prepared by bringing together a solution of sulfur dichloride and concentrated solutions of thiosulfate in an acid medium at about 0°C. and then neutralizing with potassium hydroxide (in methanol solution) (40). If sulfur monochloride is taken as the starting material, *potassium tetrathionate* (84) and *potassium hexathionate* (40) can be similarly prepared. Sulfur monobromide, sulfur monothiocyanate, $S_2(SCN)_2$ (38), or dithioamines, $S_2(NR_2)_2$ (94), can be used instead of sulfur monochloride. (See also ref. (93).) A dithioamine yields according to equation (30) the tetrathionate of the secondary amine used. The processes can be used not only for the preparation of potassium and alkylammonium salts, but also for the preparation of polythionic salts in general. Thus, for example, the piperidinium salt of hexathionic acid was made according to equation (32) from sulfur monochloride and piperidinium thiosulfate in chloroform (33).

Reaction Between Hydrogen Sulfide and Sulfur Dioxide in an Aqueous Medium. The formation of polythionic acids from Wackenroder's liquid, the reaction product of hydrogen sulfide with sulfur dioxide in an aqueous solution, is today still of practical value (see under "Applications"). Debus found that the different polythionates are formed in varying amounts according to the pH of the solution and the concentrations of the starting materials. If excess hydrogen sulfide is used, sulfur is the chief product together with a small amount of pentathionate (18,80); if 1 mole of hydrogen sulfide and 2 moles of sulfur dioxide are brought together in an acid medium, chiefly *tetrathionic acid* is formed (56). With hydrogen sulfide and neutral HSO_3^- solution, 4 moles of HSO_3^- are used per mole of hydrogen sulfide, and equimolar quantities of thiosulfate and *trithionate* are formed (55,95). If instead of hydrogen sulfide, sodium hydrogen sulfide is treated with HSO_3^-, the formation of polythionate stops and thiosulfate is formed (26,28,92):

$$2\,NaHS + 4\,NaHSO_3 \longrightarrow 3\,Na_2S_2O_3 + 3\,H_2O \qquad (33)$$

A mechanism for the reactions, based on equations (29–32), has been proposed by Stamm and Goehring (83).

Oxidation of Thiosulfuric Acid (*q.v.*) **and Thiosulfates.** *Tetrathionates* can be prepared by oxidation of thiosulfate in weakly acid to neutral solution with iodine, copper(II) salts, dichromate, peroxydisulfate (76), cyanogen iodide or bromide, nitrous acid, or hydrogen peroxide:

$$2\,S_2O_3^{2-} + I_2 \longrightarrow S_4O_6^{2-} + 2\,I^- \qquad (34)$$

$$2\,S_2O_3^{2-} + S_2O_8^{2-} \xrightarrow{Cu} 2\,SO_4^{2-} + S_4O_6^{2-} \qquad (35)$$

Anodic oxidation of thiosulfate also gives polythionate (12).

Trithionates can be prepared by oxidation of thiosulfate with hydrogen peroxide in an alkaline solution (90); in this reaction also, tetrathionate is formed first and then is decomposed by the alkali (79).

Hexathionates are prepared by reaction of thiosulfate with nitrite in acid solution (77,89). In this reaction NO_2^- is reduced to N_2O, NO, and N_2 (75).

Disproportionation of Sulfurous Acid Derivatives. Concentrated solutions of ammonium hydrosulfide decompose explosively with the intermediate formation of polythionic acids (15). An analogous decomposition of sulfurous acid occurs with

noticeable speed only at 150°C. (27); it is catalyzed by iodide and selenium dioxide. These reactions result mainly in the formation of *trithionate*. The reaction product from sulfur dioxide and ammonia, $SO_2 . NH_3$ (44), disproportionates faster with the formation of trithionate than does ammonium hydrogen sulfite or sulfurous acid. The reaction produces sulfate and imidodisulfonate, $[HN(SO_3)_2]^{2-}$, besides trithionate.

Decomposition of Thiosulfuric Acid. Thiosulfate ion reacts with hydrogen ions (30) according to equations (36–38). The solutions of these substances can then react slowly to form polythionate and hydrogen sulfide. The extent of formation of polythionate depends greatly on the pH value of the solution (57,78). The manner in which polythionic acids are formed from thiosulfuric acid has not been explained (13,45). Catalysts like As^{III}, Sb^{III}, and to a smaller extent, also Sn^{IV}, Bi^{III}, and Mo^{VI} can so influence the reaction that 95% of the sulfur of the thiosulfate is changed to polythionate sulfur (68). According to the pH of the solution, different polythionic acids can thus be prepared. Procedures have been worked out for the preparation of *potassium pentathionate* (79), *tri-* and *tetrathionate* (72), and *hexathionate* (64,73). The formation of polythionic acids presumably takes place in such a way that from As^{III} and $S_2O_3^{2-}$ there is first formed a complex, $[As(S_2O_3)_3]^{3-}$ (29), which reacts further to form polythionates (52,54).

$$S_2O_3^{2-} + H^+ \rightleftharpoons HS_2O_3^- \qquad (36)$$

$$HS_2O_3^- \rightleftharpoons HSO_3^- + S \qquad (37)$$

$$S_2O_3^{2-} + SO_2 \rightleftharpoons [S_2O_3(SO_2)]^{2-} \qquad (38)$$

Other Reactions. Polythionic acids are formed to a small extent when elementary sulfur is exposed to air and moisture; this formation has been noted particularly in the hydrolysis of overheated sulfur vapor (47). In a similar manner, polythionic acids are formed in the hydrolysis of S_4N_4 (39), $S_4(NH)_4$ (39), and S_7NH (43). Solutions of the free polythionic acids are obtained from solutions of the potassium polythionates by precipitation of the potassium salts of tartaric, fluosilicic, or perchloric acid with the calculated amount of one of these acids.

Applications

Only a few references to the practical use of thionates can be found in the literature. In the so-called *Walter Feld process* (115) the polythionates were suggested as an intermediate step in the removal of hydrogen sulfide from gas. However, neither this process nor variations (116,118) of it have been adopted commercially.

In 1922 Young (112) suggested that pentathionic acid was the fungicidal factor accompanying sulfur when sulfur was used in agricultural sprays and dusts and later patented a colloidal sulfur preparation (117) which he claimed contained a high percentage of pentathionic acid. The fungicidal factor of sulfur has proved to be a highly controversial subject. A number of publications (100,101,109) confirmed Young's theory (102,111,113,114), while others (107,110) held that the polythionic acids were no more toxic than could be expected from the hydrogen ions alone. Parker-Rhodes found that only certain sulfur compounds, and not the thionates, would be absorbed by spores (105). The polythionates as such have not found any use in agricultural sprays.

Polythionate solutions were introduced by Neesby (120) in 1940 for dermatological and cosmetic applications instead of suspensions of elemental sulfur and organic sulfur compounds. These solutions consist of aqueous solutions of pH 1 of approxi-

mately equal amounts of penta- and tetrathionates (total 5% polythionates). The solutions are stabilized by the presence of small amounts of cupric salts (0.0005 molarity of cupric acetate). These solutions are stable even at elevated temperature but will decompose if exposed to sunlight or other ultraviolet sources. They are prepared by a modification of Wackenroder's process (see p. 84), since this readily yields stable solutions of polythionates without recrystallization, as required in methods based on the reaction of acids and salts. The products are marketed in the U.S. under the names Dermasulf and Thyoquent, and in Europe as Polythiosol, Dermeacneyl, and Euthiosol.

Clinical investigations showing the dermatological effect of polythionates have been published by a number of authors (96,97,103). The beneficial effect on the skin has been ascribed to (*1*) the bactericidal-bacteristatic (98,104) and fungistatic effect of polythionic acids, (*2*) the tanning and drying effect of polythionic acids on the skin, and (*3*) the decomposition of the polythionates yielding finely divided sulfur.

Solutions of sodium tetrathionate (119) were used intravenously against thromboangiitis obliterans by Theis and Freeland (108), but the application was discontinued after some years (99).

Encouraging results have been reported in Spain with sodium trithionate in the treatment of tuberculous infections of the lung (106).

Bibliography

DITHIONIC ACID

(1) Barnes, W. H., and Wendling, A. V., *Z. Krist.*, **99**, 153 (1938).
(2) Bassett, H., and Parker, W. G., *J. Chem. Soc.*, **1951**, 1540.
(3) Haber, F., *Naturwiss.*, **19**, 452 (1931).
(4) Ishikawa, X., and Hagisawa, H., *Sci. Rep. Tohoku Imp. Univ.*, (I) **21**, 484 (1932).
(5) Pfanstiel, R., in Fernelius, *Inorganic Syntheses*, Vol. 2, p. 167, McGraw-Hill, N.Y., 1946.
(6) Stamm, H., and Goehring, M., *Z. physik. Chem.*, **A183**, 89 (1938).
(7) Stamm, H., and Goehring, M., *Z. physik. Chem.*, **A183**, 112 (1938).
(8) Stamm, H., and Goehring, M., *Z. physik. Chem.*, **A183**, 241 (1939).
(9) Tammann, G., and Boehme, W., *Z. anorg. u. allg. Chem.*, **204**, 143 (1932).
(10) Yost, D. M., and Pomeroy, R., *J. Am. Chem. Soc.*, **49**, 703 (1927).

POLYTHIONIC ACIDS

(11) Abegg, *Handbuch der anorganischen Chemie*, S. Herzel, 1927, Vol. IV, Pt. 1, p. 556.
(12) Bancroft, W. D., *Trans. Electrochem. Soc.*, **71**, 195 (1937).
(13) Bassett, H., and Durrant, H. G., *J. Chem. Soc. London*, **1927**, 1401.
(14) Baumgarten, P., *Ber.*, **65**, 1637 (1932).
(15) Bosch, C., *Z. Elektrochem.*, **24**, 365 (1918).
(16) Christiansen, I. A., and Drost-Hansen, W., *Nature*, **164**, 759 (1949).
(16a) Croatto, U., Scatturin, V., and Fava, A., *Ricerca sci.*, **19**, 700 (1950).
(16b) Day, A. L., and Allen, E. T., *Carnegie Inst. Publ.*, No. **360** (1925).
(17) Deines, O. v., and Christoph, E., *Z. anorg. u. allgem. Chem.*, **213**, 209 (1933).
(18) Deines, O. v., and Grassmann, H., *Z. anorg. u. allgem. Chem.*, **220**, 337 (1934).
(19) Eucken, M., and Wagner, J., *Acta Phys. Austriaca*, **1**, 379 (1948).
(20) Faessler, A., and Goehring, M., *Naturwiss.*, **39**, 169 (1952).
(21) Feikes, L., Dissertation, Heidelberg, 1953.
(22) Feld, W., *Z. angew. Chem.*, **25**, 705 (1912).
(23) Foerster, F., and Centner, K., *Z. anorg. u. allgem. Chem.*, **157**, 45 (1926).
(24) Foerster, F., and Haufe, E., *Z. anorg. u. allgem. Chem.*, **177**, 17 (1929).
(25) Foerster, F., and Hornig, A., *Z. anorg. u. allgem. Chem.*, **125**, 86 (1922).

(26) Foerster, F., and Kircheisen, E., *Z. anorg. u. allgem. Chem.*, **177**, 42 (1928).
(27) Foerster, F., Lange, F., Drossbach, O., and Seidel, W., *Z. anorg. u. allgem. Chem.*, **128**, 245 (1923).
(28) Foerster, F., and Mommsen, E. Th., *Ber.*, **57**, 258 (1924).
(29) Foerster, F., and Stühmer, G., *Z. anorg. u. allgem. Chem.*, **206**, 1 (1932).
(30) Foerster, F., and Vogel, R., *Z. anorg. u. allgem. Chem.*, **155**, 161 (1926).
(31) Foss, O., *Kgl. Norske Videnskab. Selskabs Forh.*, **14**, No. 20, 75 (1941).
(32) Foss, O., *Kgl. Norske Videnskab. Selskabs Forh.*, **16**, No. 20, 72 (1943).
(33) Foss, O., *Kgl. Norske Videnskab. Selskabs Skrifter*, **1945**, No. 2, (1947).
(34) Foss, O., *Kjemi Bergvesen og Metallurgi*, **1**, 6 (1946).
(35) Foss, O., *Acta Chem. Scand.*, **6**, 802 (1952).
(36) Foss, O., *Acta Chem. Scand.*, **7**, 230 (1953).
(37) Foss, O., *Acta Chem. Scand.*, **7**, 697 (1953).
(37a) Foss, O., Furberg, S., and Zachariasen, H., *Acta Chem. Scand.*, **8**, 459 (1954); Foss, O., and Zachariasen, H., *ibid.*, 473.
(37b) Gmelin, 8th ed., System-Nummer 9, Teil X, 1955. In press.
(38) Goehring, M., *Ber.*, **76**, 742 (1943).
(39) Goehring, M., *Ber.*, **80**, 110 (1947).
(40) Goehring, M., and Feldmann, U., *Z. anorg. u. allgem. Chem.*, **257**, 223 (1948).
(41) Goehring, M., Feldmann, U., and Helbing, W., *Z. anal. Chem.*, **129**, 346 (1949).
(42) Goehring, M., Helbing, W., and Appel, I., *Z. anorg. u. allgem. Chem.*, **254**, 185 (1947).
(43) Goehring, M., Herb, H., and Koch, W., *Z. anorg. u. allgem. Chem.*, **264**, 137 (1951).
(44) Goehring, M., and Kaloumenos, H. W., *Z. anorg. u. allgem. Chem.*, **263**, 137 (1950).
(45) Goehring, M., *Fortschr. chem. Forsch.*, **2**, 444 (1952).
(46) Guittonneau, G., and Keiling, J., *Compt. rend.*, **195**, 679 (1932).
(47) Gutbier, A., *Z. anorg. u. allgem. Chem.*, **152**, 163 (1926).
(48) Gutmann, A., *Ber.*, **40**, 3614 (1907).
(49) Gutmann, A., *Ber.*, **41**, 300 (1908).
(50) Haber, F., *Naturwiss.*, **19**, 452 (1931).
(51) Hansen, C. J., *Ber.*, **66**, 817 (1933).
(52) Hansen, C. J., *Ber.*, **66**, 1000 (1933).
(53) Hansen, C. J., *Ber.*, **66**, 1009 (1933).
(54) Hansen, C. J., *Ber.*, **67**, 1418 (1934); **72**, 535 (1939).
(55) Hansen, C. J., and Werres, H., *Chem.-Ztg.*, **57**, 25 (1933).
(56) Janickis, J., *Z. anorg. u. allgem. Chem.*, **225**, 177 (1935).
(57) Janickis, J., *Z. anorg. u. allgem. Chem.*, **234**, 193 (1937).
(58) Jellinek, I. K., *Z. physik. Chem.*, **76**, 257 (1911).
(59) Kolthoff, I. M., *Rec. trav. chim.*, **43**, 216 (1924).
(60) Kurtenacker, A., *Z. anorg. u. allgem. Chem.*, **116**, 243 (1921).
(61) Kurtenacker, A., *Z. anorg. u. allgem. Chem.*, **134**, 265 (1924).
(62) Kurtenacker, A., *Analytische Chemie der Sauerstoffsäuren des Schwefels*, Enke, Stuttgart, 1938.
(63) Kurtenacker, A., and Bittner, A., *Z. anorg. u. allgem. Chem.*, **142**, 119 (1924).
(64) Kurtenacker, A., and Czernotzky, A., *Z. anorg. u. allgem. Chem.*, **174**, 179 (1928).
(65) Kurtenacker, A., and Fluss, W., *Z. anorg. u. allgem. Chem.*, **210**, 125 (1933).
(66) Kurtenacker, A., and Fritsch, A., *Z. anorg. u. allgem. Chem.*, **117**, 202, 262 (1921).
(67) Kurtenacker, A., and Goldbach, E., *Z. anorg. u. allgem. Chem.*, **166**, 177 (1927).
(68) Kurtenacker, A., and Ivanow, I. A., *Z. anorg. u. allgem. Chem.*, **185**, 337 (1930).
(69) Kurtenacker, A., and Kaufmann, M., *Z. anorg. u. allgem. Chem.*, **148**, 43 (1925).
(70) Kurtenacker, A., and Kaufmann, M., *Z. anorg. u. allgem. Chem.*, **148**, 256 (1925).
(71) Kurtenacker, A., and Kaufmann, M., *Z. anorg. u. allgem. Chem.*, **148**, 369 (1925).
(72) Kurtenacker, A., and Matejka, K., *Z. anorg. u. allgem. Chem.*, **193**, 367 (1930).
(73) Kurtenacker, A., and Matejka, K., *Z. anorg. u. allgem Chem.*, **229**, 19 (1936).
(74) Kurtenacker, A., Mutschin, A., and Stastny, F., *Z. anorg. u. allgem. Chem.*, **224**, 399 (1935).
(75) Kurtenacker, A., and Spielhaczek, H., *Z. anorg. u. allgem. Chem.*, **217**, 321 (1934).
(76) Mackenzie, J. E., and Marshall, H., *J. Chem. Soc. London*, **93**, 1726 (1908).
(77) Partington, J. R., and Tipler, A. F., *J. Chem. Soc. London*, **1929**, 1382.
(78) Prakke, F., and Stiasny, E., *Rec. trav. chim.*, **52**, 615 (1933).

(79) Raschig, F., *Schwefel- und Stickstoffstudien*, Verlag Chemie, Berlin and Leipzig, 1924.
(80) Riesenfeld, E. H., and Feld, G. W., *Z. anorg. u. allgem. Chem.*, **119**, 225 (1921).
(81) Sander, A., *Chem.-Ztg.*, **41**, 657 (1917).
(82) Schuleck, E., *Z. anal. Chem.*, **68**, 391 (1926).
(83) Stamm, H., and Goehring, M., *Z. angew. Chem.*, **58**, 52 (1945).
(84) Stamm, H., Goehring, M., and Feldmann, U., *Z. anorg. u. allgem. Chem.*, **250**, 226 (1942)
(85) Stamm, H., Seipold, O., and Goehring, M., *Z. anorg. u. allgem. Chem.*, **247**, 277 (1941).
(86) Spohn, K., Dissertation, Halle, 1930.
(87) Warren, B. E., and Burwell, J. T., *J. Chem. Phys.*, **3**, 6 (1935).
(88) Weiser, H. B., *Inorganic Colloid Chemistry*, Wiley, N.Y., 1933, Vol. I, p. 305.
(89) Weitz, E., and Achterberg, F., *Ber.*, **61**, 399 (1928).
(90) Willstätter, R., *Ber.*, **36**, 1831 (1903).
(91) Zachariasen, W. H., *Z. Krist.*, **89**, 529 (1934).
(92) Ger. Pat. 380,756 (1923), E. C. Marburg.
(93) Ger. Pat. 400,192 (1925), Weiler ter Mer.
(94) Ger. Pat. 520,857 (1930), H. Lecher and T. Weigel.
(95) Ger. Pat. 527,956 (1931), I. G. Farbenind.

APPLICATIONS

(96) Delaney, J. R., and Mahood, J. J., *J. Michigan State Med. Soc.*, **50**, 1236–38 (1951).
(97) Finnerud, C. W., and Riddell, J. M., Jr., *Arch. Dermatol. and Syphilol.*, **63**, 373–75 (1951).
(98) Hoeden, J. van der, *Ned. Tijdschr. Hyg. Microbiol. Serol.*, **6**, 247 (1932).
(99) *J. Am. Med. Assoc.*, Council on Pharmacy and Chemistry, **133**, 693–94 (1947).
(100) Lee, H. A., and Martin, J. P., *Science*, **66**, 178 (1927).
(101) Liming, O. N., *Phytopathology*, **21**, 131 (1931); **22**, 143 (1932); **23**, 155 (1933).
(102) Liming, O. N., and Young, H. C., *J. Agr. Research*, **40**, 951 (1930).
(103) Moller, P., and Lomholt, S., *Acta Dermato-Venereol.*, **26**, 169–74 (1945).
(104) Moller, P., and Pedersen, A., *Acta Pathol. Microbiol. Scand.*, **21**, 596 (1944).
(105) Parker-Rhodes, A. F., *Ann. Appl. Biol.*, **29**, 136 (1942).
(106) Pena, I. B., *Medicina Clinica (Spain)*, **8**, 217–31 (1947).
(107) Roach, W. A., and Glynne, M. D., *Ann. Appl. Biol.*, **15**, 168 (1928).
(108) Theis, F. V., and Freeland, M. R., *Arch. Surg.*, **40**, 190 (1940).
(109) Tisdale, L. E., *Ann. Missouri Botan. Garden*, **12**, 381–418 (1925).
(110) Wilcoxon, F., and McCallan, S. E. A., *Phytopathology*, **20**, 391 (1930).
(111) Williams, R. C., and Young, H. C., *Ind. Eng. Chem.*, **21**, 359 (1929).
(112) Young, H. C., *Ann. Missouri Botan. Garden*, **9**, 403–35 (1922).
(113) Young, H. C., and Liming, O. N., *Bull. Ohio Agr. Expt. Sta., 48th Ann. Rept.*, **446**, 61 (1930).
(114) Young, H. C., and Williams, R. C., *Science*, **67**, 19 (1928).
(115) U.S. Pat. 985,667 (Feb. 28, 1911), W. Feld.
(116) U.S. Pat. 1,832,325 (Nov. 17, 1931), L. Rosenstein.
(117) U.S. Pat. 1,917,351 (July 11, 1933), H. C. Young.
(118) U.S. Pat. 2,241,709 (May 13, 1941), N. Levy.
(119) U.S. Pat. 2,439,720 (April 13, 1948), R. W. Crosley, H. Crest, and A. L. Raymond (to Searle & Co.).
(120) U.S. Pat. 2,551,627 (May 8, 1951), reissue 23,771 (Sept. 8, 1953), T. E. Neesby (to Carroll Dunham Smith Pharmacal Co.).

MARGOT GOEHRING
T. E. NEESBY (Applications)

THIONIUM COMPOUNDS. See *Onium compounds; Sulfur compounds, organic,* Vol. **13,** p. 440.

THIONYL HALIDES, SOX_2. See *Sulfur compounds, inorganic,* Vol. **13,** p. 405.

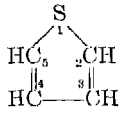
THIOPENTAL, $C_{11}H_{18}N_2O_2S$. See *Stimulants and depressants of the nervous system,* Vol. **13,** p. 10.

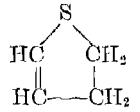
THIOPHANIUM DERIVATIVES. See *Stimulants and depressants of the nervous system,* Vol. **13,** p. 36.

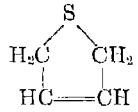
THIOPHENE

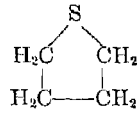
Thiophene (thiofuran, divinylene sulfide), C_4H_4S, formula weight 84.14, is a colorless, water-insoluble cyclic sulfur compound with a benzenelike odor.

The structural formulas of thiophene and the dihydro- and tetrahydrothiophenes are usually represented as follows.


Thiophene


2-Thiolene


3-Thiolene


Thiolane

The older nomenclature referred to the 2- and 5- positions as the α- and α'- positions, and to the 3- and 4- positions as β- and β'- positions. The two isomeric radicals C_4H_3S— formed by removing one hydrogen from the thiophene formula are named *2-* and *3-thienyl.* The two thienylmethyl radicals, $C_4H_3SCH_2$—, are referred to as *2-* and *3-thenyl.* The radicals C_4H_3SCO— derived from the two thiophenecarboxylic acids are called *2-* and *3-thenoyl.*

Commercially, thiophene is still in the market development stage. Several thiophene-based antihistaminics have been marketed under various brand names, a thiophene-based antispasmodic has shown promise, and other thiophene-derived pharmaceuticals have been studied. Thiophene-based resins, dyes, agricultural chemicals, economic poisons, and inhibitors are in various stages of development.

Thiophene was first recognized as a chemical individual by Victor Meyer in 1882 when the characteristic indophenine test for benzene which he was demonstrating failed. He found that his assistant, T. Sandmeyer, had given him benzene prepared by dry distillation of calcium benzoate, instead of commercial benzene. Meyer found that when commercial benzene was scrubbed with sulfuric acid, the indophenine test became weak. From the sulfonic acid extract so obtained Meyer regenerated thiophene, which he found to be the component responsible for the indophenine test. He then established the structure of thiophene and eventually synthesized the compound by ring closure of succinic acid with phosphorus pentasulfide. In 1888 Meyer published his book on thiophene after five years of intensive research. The first synthetic thiophene derivative reported in the literature, by Laurent in 1844, was definitely proved to be tetraphenylthiophene (*thionessal*), $C_4S(C_6H_5)_4$, in 1891 when Bauman and coworkers synthesized it by ring closure of stilbene, $C_6H_5CH{=}CHC_6H_5$, with sulfur at 250°C. In 1910 Wilhelm Steinkopf started a study of thiophene chemistry which lasted several decades, culminating in the publishing of his book (23). The present commercial process for thiophene by the reaction of butane with sulfur, announced in 1945, made thiophene available at a reasonable price and started another period of

very active thiophene research. Most of the work which is summarized in this article is taken from this latter period.

Properties

CONSTANTS

Following are the more important physical constants of thiophene: b.p. 84.12°C.; f.p. −38.30°C.; d_4^{25} 1.0583; n_D^{25} 1.5256; η^{25} 0.621 centipoises; crit. temp. 310°C.; crit. pressure 45 atm.; heat of vaporization 7760 cal./mole; heat of formation (liquid) $\Delta H = -19.6$ kg.-cal./mole; heat of combustion 670 kg.-cal./mole; heat of fusion 14.11 cal./g.; vapor pressure 500 mm. Hg 71°C., 700 mm. Hg 81.5°C., 900 mm. Hg 89.7°C.

Thiophene is soluble in hydrocarbons and in most of the common organic solvents, but is immiscible with water. Thiophene and benzene form solid solutions at all concentrations, so that their separation by crystallization is impractical.

The molecular structure and spectroscopy of thiophene and its derivatives have been thoroughly reviewed (12). The thiophene ring is planar, and the nuclei of the five atoms are spaced about an axis of symmetry which passes through the sulfur nucleus. The electronic structure contains mobile electrons from the conjugated double bonds which, with some electrons from the decet possible about the sulfur atom, exert great influence upon the chemical properties of the molecule.

Infrared and mass spectrographic methods have been useful techniques for analytical work. The infrared spectrogram of pure thiophene along with those of several of the closer members of the thiophene family are given in (10).

REACTIONS

Thiophene is less stable than benzene. Ring rupture with evolution of hydrogen sulfide begins at about 200°C. in the presence of various clays, alumina, and silica-alumina catalysts. Sulfur dioxide is evolved during polymerization processes with sulfuric acid. Potassium ruptures the ring, forming potassium sulfide, whereas sodium is inactive. Alkyl and aryl derivatives of thiophene are in general more stable than thiophene itself, the most stable being apparently tetraphenylthiophene, which boils at about 460°C.

Ozone in oxygen bubbled through a suspension of thiophene in water is said to form an ozonide. Thiophene auto-oxidizes with air in light, forming sulfuric and oxalic acids. Hydrogen peroxide is said to form products of undetermined structure with thiophene; with tetraphenylthiophene it forms the 1,1-dioxide, a cyclic sulfone, but other thiophene dioxides have been prepared by cyclization of conjugated diolefins and sulfur dioxide. See *Sulfones*, Vol. **13**, p. 342.

Thiophene undergoes most typical aromatic substitution reactions more rapidly than does benzene. Certain reactions, such as aminomethylation, chloromethylation, and mercuration, which fail or proceed slowly with benzene, go rapidly with thiophene. Except in the special case of alkylation, monosubstitution occurs almost exclusively in the 2- position. Disubstitution occurs predominantly in the 2- and 5- positions.

Halogenation (10, pp. 173–84). Thiophene reacts rapidly with chlorine at temperatures ranging from −30°C. to its boiling point, 84°C. Substitution apparently is the main reaction until 2,5-dichlorothiophene is formed. After that, addition predominates. All of the possible substitution products can be obtained by dehydro-

chlorination of the addition products. Thiophene and sulfuryl chloride, SO_2Cl_2, yield 2-chlorothiophene. *N*-Chloroacetamide and thiophene yield a mixture of 2-chloro- and 2,5-dichlorothiophenes. Chlorine derivatives of thiophene ranging from 2- and 3-chlorothiophenes to 2,2,3,3,4,4,5,5-octachlorothiolane have been described.

Thiophene is brominated by bromine, cyanogen bromide, *N*-bromosuccinimide, etc. (10, p. 200).

Thiophene iodinates with iodine and mercuric oxide. In benzene solution in the cold, 2-iodothiophene is formed. In glacial acetic acid under reflux, tetraiodothiophene is obtained (10, pp. 210–12).

Acylation. Thiophene is readily acylated to give thienyl ketones. The classic technique of acylation with an acyl halide and aluminum chloride works well. Catalytic amounts of strong inorganic acids of sulfur and phosphorus promote acylation of thiophene with acid anhydrides:

$$(RCO)_2O + C_4H_4S \longrightarrow RCOC_4H_3S + RCOOH$$

Thiophene has been acylated with carboxylic acids in the presence of molar amounts of phosphorus pentoxide (10, pp. 321–31).

The 2-thienyl methyl ketones (obtained by acetylating thiophenes) readily undergo the haloform reaction with sodium hypochlorite to yield the 2-thiophenecarboxylic acids (11).

Aminomethylation. Thiophene reacts with formaldehyde and ammonium chloride. Depending upon conditions, several products can be obtained, such as the dimer of *N*-2-thenylformaldimine $(C_4H_3SCH_2N{=}CH_2)_2$, mono-, di- and tri-2-thenylamines. The aminomethylation reaction takes place with ammonium halides, but other ammonium salts fail to react. The use of hydroxylamine salts instead of ammonium salts gives the various *N*-2-thenylhydroxylamines. Under controlled conditions, this reaction yields nitrogenous resins soluble or dispersible in acids, insoluble in bases (10, pp. 244–51).

Metalation. 2-Thienyllithium is formed from thiophene and butyllithium in ether (3). 2-Thienylsodium is readily formed by transmetalation of thiophene with sodium amalgam and an alkyl or aryl halide in refluxing ether (22). 2-Thienylsodium is also formed in good yield from 2-chlorothiophene and sodium amalgam in benzene; in ether, however, 5-chloro-2-thienylsodium is formed (21). The thienylsodiums are readily carbonated to the carboxylic acids. In general, they undergo the Grignard-type reactions.

Thiophene is converted into 2-thiophenemercurichloride (2-(chloromercuri)thiophene), C_4H_3SHgCl, and the 2,5-dimercurichloride on treatment with mercuric chloride in dilute alcoholic solution. Mercuric acetate reacts with thiophene to form polymercuriacetates. The 2,5-dimercuriacetate is formed in 50% acetic acid at 50°C., and the tetramercuriacetate is formed in glacial acetic acid at 80–90°C. (10, pp. 445–49).

Alkylation. Direct alkylation of thiophene with olefins produces the 2- and 3-alkylthiophenes in about equal proportions. Ethylene does not react, propylene reacts with difficulty, but higher olefins alkylate thiophene readily in the presence of suitable catalysts. Many catalysts such as active clays, boron fluoride complexes, sulfuric acid, aluminum chloride, hydrogen fluoride, have been used (10, pp. 162–63). The Clemmensen method (reduction of a thienyl alkyl ketone) has been widely used for the preparation of 2-alkylthiophenes (10, p. 160).

Polymerization and Resinification. Thiophene is readily polymerized by sulfuric acid, hydrogen fluoride, ferric chloride, stannic chloride, aluminum chloride, etc. Mild polymerizing agents, such as silica-alumina gels, and 100% orthophosphoric acid, yield trimeric and pentameric substances. The trimer has been identified as 2,4-di-2-thienylthiolane (15). The alkylthiophenes also polymerize under the same conditions.

Thiophene condenses with formaldehyde under mildly acidic conditions to form thermoplastic and thermosetting resins. Bases do not catalyze the reaction. However, thiophene-phenol co-condensation products with formaldehyde will thermoset at an alkaline pH in the presence of hexamethylenetetramine (10, p. 162).

Sulfonation. Thiophene is readily converted to 2-thiophenesulfonic acid by treatment with 95% sulfuric acid or with chloro- or fluorosulfonic acid (10, p. 418; 25). The 3-sulfonic acid has been prepared by brominating the 2- and 5- positions, sulfonating, and then debrominating.

Nitration. The mixed-acid nitration technique suitable for benzene is too severe for thiophene, but yields of 70% or more of 2-nitrothiophene can be obtained by adding thiophene dissolved in acetic anhydride to a solution of nitric acid in glacial acetic acid at 10°C. (2). Benzoyl nitrate and cold thiophene are said to give almost quantitative yields of 2-nitrothiophene.

Although the nitrothiophenes can be reduced to the aminothiophenes, the latter are unstable in the presence of air. They can be stored only in an inert atmosphere or as double salts, etc.

Occurrence and Production

Thiophene is present in the crude benzene fraction of coal tar distillate to the extent of about 0.5% wt. Thiophene and derivatives have also been found in varying quantities in carbonaceous deposits of lignite, peat, shale, coal, and certain crude oils. It is not known whether thiophene exists naturally in crude oils or whether it is formed during high temperature distillation or other processing. Certain shale oils have been found to be high in thiophene content. Picon (18) has described methods of separation of thiophene and its homologs from shale oils obtained in the Tyrol and in the Ain district of France. These oils contain up to 16% sulfur mostly in the form of thiophene and thiophene derivatives. These methods of recovery were not known to have been commercialized to any extent until recently (7).

Thiophene has been made by reaction between various hydrocarbons and sulfur or sulfur compounds. The yields from these reactions are sometimes poor and a variety of other compounds are formed. A commonly used laboratory synthesis employing succinic anhydride and phosphorus heptasulfide (P_4S_7) gives good yields of thiophene (17). The best means to date for the production of thiophene involves the reaction of straight-chain C_4 hydrocarbons with sulfur thermally (24) or with hydrogen sulfide over a catalyst (27) or with sulfur dioxide (28) over a catalyst. Thus far only one of these processes, the noncatalytic reaction of *n*-butane and sulfur at 600°C., has been developed sufficiently to be a commercial source of thiophene (20). The yield is about 40%, and about the same percentage of a tar is formed, containing 3-thiophenethiol, C_4H_3SSH, b.p. 171.1°C., d^{25} 1.251, and a red liquid $C_4H_4S_3$, b.p.$_2$ 120–25°C., which may be a thiolanedithione (6).

Methyl derivatives of thiophene may also be prepared by this process by using pentane in place of butane. Thus *n*-pentane produces 2-methylthiophene, b.p.

112.5°C., d_4^{20} 1.0194, whereas isopentane produces 3-methylthiophene, b.p. 115.4°C., d_4^{20} 1.0216.

In the Socony-Vacuum thiophene process, as practiced on a semicommercial scale from 1946 to 1952, sulfur of ordinary commercial grade is melted and pumped through an alloy coil in a gas-fired furnace where it is vaporized and heated to about 700°C. *n*-Butane fresh feed and C_4 hydrocarbon recycle, consisting of unreacted butane, butylenes, and butadiene, are pumped through a second coil where the combined hydrocarbon stream is heated to about 560°C. The *n*-butane purity required is 95% or better. The impurity usually present in ordinary commercial grade *n*-butane is predominantly isobutane. In an early version of the process the heated streams of sulfur and C_4 were mixed and passed through a coil reactor in a third furnace. Subsequently the reactor consisted simply of a section of insulated pipe acting as an adiabatic reactor. The reaction is endothermic, and the reaction temperature is about 560°C. average and the reaction time about two seconds.

The reactor effluent is passed into a chamber where it is quenched with a water spray. This arrests the reaction and condenses most of the by-product tar formed. Tar and quench water settle in two layers at the bottom of the quench tower and are continuously withdrawn; the overhead passes through a glass-wool filter to remove entrained tar mist. The filtered gas is then cooled to room temperature and fed into a gas separator where condensed liquid is collected.

The gas from the separator is compressed to about 180 p.s.i.g. and is then cooled and discharged into a surge tank where it is combined with the liquid which is pumped from the gas separator. Liquid and noncondensed gases are fed to a stabilizer tower.

The stabilizer tower removes components lighter than C_4 which are rejected from the process. The overhead from this tower contains about 80 mole per cent hydrogen sulfide and 20 mole per cent light hydrocarbons. This stream may be processed further to recover the sulfur. Under typical operating conditions the stabilizer reboiler is maintained at 200°F. and temperature at the top is about 75°F. The pressure is normally about 165 p.s.i.g.

The bottoms from the stabilizer tower are fed into a debutanizer tower where unreacted C_4 constituents are removed overhead. This tower operates at about 65 p.s.i.g. with a top temperature of 135°F. and a reboiler temperature of 300°F. The overhead consists of about 70 mole per cent butane, 20 of butylenes, 10 of butadiene, and minor amounts of thiophene, carbon disulfide and light ends. These are fed back to the process as recycle stream. The bottoms, which constitute the crude thiophene stream, contain about 80 mole per cent thiophene and 15 mole per cent carbon disulfide. These are withdrawn from the process to storage for batch distillation to recover thiophene. The thiophene thus recovered is in excess of 99% pure.

In processing 100 lb. of butane about 270 lb. of sulfur are required and the following products are made: thiophene, 70 lb.; hydrogen sulfide, 184 lb.; carbon disulfide, 10 lb.; tar, 80 lb. The tar can be further vacuum- or steam-distilled to produce about 15 lb. of 3-thiophenethiol. The balance of the tar and the hydrogen sulfide can be processed to recover about 200 lb. of the 270 lb. of sulfur initially used.

Economic Aspects. During its semicommercial manufacture thiophene commanded a selling price that permitted its use in the pharmaceutical industry in commercial quantities. However, in the more price-sensitive fields such as solvents, resins, agricultural chemicals, and dyes no large scale uses have occurred to date. The results of exploratory research in these fields, however, presage that larger, more

diversified markets for thiophene will eventually be developed. The economics of the reaction of *n*-butane with sulfur are such that increased production will result in a definite decrease in price.

Specifications and Methods of Testing. The specifications established for thiophene during its experimental manufacture are as follows: boiling range (760 mm.) (ASTM Method D86-40); i.b.p., 83°C.; 99%, 85 °C.; cottrell b.p., 84 to 85 °C.; f.p., −38 to −36°C.; density, 1.064; refractive index n_D^{20}, 1.5284 to 1.5290; purity (by f.p.), 99% min.

No standardized test procedures have been developed for thiophene. Those suggested by the specifications listed above as well as spectrographic methods have been used to date to control quality.

Thiophene may be estimated when present in small quantities such as in benzene by a colorimetric procedure involving comparison of the color developed by an isatin-ferric chloride-sulfuric acid reagent with color standards made from known concentrations in benzene (1). A recommended procedure for determining purity of possible commercial grades of thiophene in lieu of specifications is by sulfur analysis and determination of the true boiling point distillation curve. Spectrographic methods of analysis can also be applied as described earlier.

Health and Safety Factors. Reviews of the biological and pharmacological activity of thiophene and its derivatives have been published (4,5). Pure thiophene, administered by inhalation, is said to be more toxic to mice than benzene (9). In the semicommercial manufacture of thiophene, the rigid observance of precautions equivalent to those employed in the handling of benzene was enforced.

Uses

Soon after the discovery and characterization of thiophene, the similarity of several of the physical and chemical properties of thiophene and its derivatives to those of the corresponding benzene compounds inspired studies of comparative biochemical and pharmaceutical properties. Thiophene analogs of about all of the important benzene-derived therapeutic agents have been prepared (5).

The thiophene compounds that have been produced commercially as therapeutic agents are antihistamine drugs. Five of a large number that have been described have been put on the market (14):

Methaphenilene.HCl, N.N.R. (Diatrine.HCl)	*N,N*-Dimethyl-*N'*-phenyl-*N'*-2-thenylethylenediamine.HCl
Methapyrilene.HCl, N.N.R. (Thenylpyramine.HCl, Thenylene.HCl, Histadyl.HCl, Semikon.HCl, etc.)	2-[(2-Dimethylaminoethyl)-2-thenylamino]pyridine.HCl (*N,N*-dimethyl-*N'*-(2-pyridyl)-*N'*-(2-thenyl)-ethylenediamine.HCl)
Thenfadil.HCl	2-[(2-Dimethylaminoethyl)-3-thenylamino]pyridine.HCl
Chloromethapyrilene citrate, N.N.R. (Chlorothen citrate, Tagathen citrate)	2-[(5-Chloro-2-thenyl)(2-dimethylaminoethyl)amino]-pyridine monocitrate
Bromothen.HCl	2-[(5-Bromo-2-thenyl)(2-dimethylaminoethyl)amino]-pyridine.HCl

All of the above compounds are tetrasubstituted ethylenediamines, one substituent of which is a thenyl (thienylmethyl) or substituted thenyl group. See also Vol. 7, pp. 470–74.

5-Phenyl-5-(2-thienyl)hydantoin sodium (Phethenylate sodium, Thiantoin sodium) has been suggested as a promising antiepileptic. See Vol. 7, p. 775.

However, those markets which would consume large quantities of thiophene with a consequent reduction in its price, are still in the development stage. The chlorothiophenes, especially 2,5-dichlorothiophene, are said to be effective grain fumigants (31). 2-Chlorothiophene is said to be a stabilizer for perchloroethylene (30). The nitrothiophenes are said to act as vapor-phase corrosion inhibitors (29). The published results of chemical-biological screening tests performed through the agency of the Chemical-Biological Coordination Center of the National Research Council show positive results with thiophene derivatives against fungi, the granary weevil, the German cockroach, lice, ticks, etc. (16). However, the thiophene analog of DDT (5-chloro-2-thienyl replacing the *p*-chlorophenyl group) was ineffective (19).

Thiophene-derived resins have received exploratory study. The polymers of thiophene are said to be vinyl resin plasticizers (26). Thiophene-formaldehyde and thiophene-phenol-formaldehyde condensation products have been described (10, p. 162). Vinylthiophene has received some attention because of its similarity to styrene.

2-Thenoyltrifluoroacetone, $C_4H_3SCOCH_2COCF_3$, has been mentioned as a coordinating agent for separating zirconium and hafnium salts (8,13).

Bibliography

(1) *ASTM Standards*, D931–47T, Suppls. 1947, pt. III-A, pp. 279–81.
(2) Babasinian, V. S., *J. Am. Chem. Soc.*, **50**, 2748 (1928).
(3) Benkeser, R. A., and Currie, R. B., *J. Am. Chem. Soc.*, **70**, 1780 (1948).
(4) Blicke, F. F., in Elderfield, *Heterocyclic Compounds*, Vol. I, pp. 221–27.
(5) Blicke, F. F., in Hartough, *Thiophene and Its Derivatives*, Interscience, New York-London, 1952, pp. 29–45.
(6) Caesar, P. D., and Branton, P. D., *Ind. Eng. Chem.*, **44**, 122 (1952).
(7) *Chem. Week*, **73**, 48 (1954).
(8) Connick, R. E., and McVey, W. H., *J. Am. Chem. Soc.*, **71**, 3182 (1949).
(9) Flury, F., and Zernik, F., *Chem. Ztg.*, **56**, 149 (1932).
(10) Hartough, H. D., *Thiophene and Its Derivatives*, Interscience, New York-London, 1952.
(11) Hartough, H. D., and Conley, L. G., *J. Am. Chem. Soc.*, **69**, 3096 (1947).
(12) Hochgesang, F. P., in Hartough, *Thiophene and Its Derivatives*, Interscience, New York-London, 1952, Chap. IV, p. 81 *et seq.*
(13) Huffman, E. H., and Beaufait, L. J., *J. Am. Chem. Soc.*, **71**, 3179 (1949).
(14) Idson, B., *Chem. Revs.*, **47**, 307 (1950).
(15) Meisel, S. L., Johnson, G. C., and Hartough, H. D., *J. Am. Chem. Soc.*, **72**, 1910 (1950).
(16) National Research Council, *Summary Tables of Biological Tests*, sponsored by the Chemical-Biological Coordination Center of the National Research Council, Washington, D.C.
(17) Phillips, R., *Organic Syntheses*, Collective Vol. II, p. 578.
(18) Picon, M., *Compt. rend.*, **228**, 251 (1948).
(19) Prill, E. H., Synerholm, M. E., and Hartzell, A., *Contribs. Boyce Thompson Inst.*, **14**, 341 (1946).
(20) Rasmussen, H. E., and Ray, F. E., *Chemistry and Industry*, **60**, 693 (1947).
(21) Schick, J. W., and Hartough, H. D., *J. Am. Chem. Soc.*, **70**, 286 (1948).
(22) Schick, J. W., and Hartough, H. D., *J. Am. Chem. Soc.*, **70**, 1645 (1948).
(23) Steinkopf, W., *Die Chemie des Thiophens*, Steinkopff, Leipzig, 1941 (lithographed by Edward Bros., Ann Arbor, Mich.).
(24) U.S. Pat. 2,450,659 (Oct. 5, 1948), R. C. Hansford, H. E. Rasmussen, and A. N. Sachanen (to Socony-Vacuum Oil Co.).
(25) U.S. Pat. 2,480,465 (Aug. 30, 1949), H. S. Halbedel and J. C. Heath (to Harshaw Chemical Co.).
(26) U.S. Pat. 2,489,674 (Nov. 29, 1949), E. P. Rittersbausen (to Socony-Vacuum Oil Co.).
(27) U.S. Pat. 2,558,507 (June, 1951), W. G. Appleby and A. F. Sarter (to Shell Development Co.).

(28) U.S. Pat. 2,570,722 (June, 1951), W. F. Sager (to The Texas Co.).
(29) U.S. Pat. 2,592,451 (April 8, 1952), R. J. Moore and A. Wachter (to Shell Development Co.).
(30) U.S. Pat. 2,621,215 (Dec. 9, 1952), R. S. Cooper (to Diamond Alkali Co.).
(31) U.S. Pat. 2,651,579 (Sept. 8, 1953), Ralph E. Plump (to Pennsylvania Salt Mfg. Co.).

D. E. BADERTSCHER AND H. E. RASMUSSEN

THIOPHENOLS, RSH. See *Mercaptans*, Vol. **8,** p. 860.

THIOPHOSGENE. See *Sulfur compounds, inorganic*, Vol. **13,** p. 386.

THIOSEMICARBAZIDE, $H_2NNHCSNH_2$; **THIOSEMICARBAZONES,** RR'C:NNHCSNH$_2$. See *Hydrazine*, Vol. **7,** pp. 586, 588.

THIOSULFONATES, RSO_2SR. See *Sulfur compounds, organic*, Vol. **13,** p. 443.

THIOSULFURIC ACID AND THIOSULFATES

Thiosulfuric acid, $H_2S_2O_3$, formula weight 114.15, is known only in solution. It is relatively unstable and decomposes into sulfur dioxide, water, and sulfur:

$$H_2S_2O_3 \longrightarrow SO_2 + H_2O + S$$

Small amounts of thiosulfates are found in the sulfur springs of the Pyrenees, in the urine of rabbits fed on white cabbage, in the residue after the explosion of gunpowder, and in the soil from the action of various soil organisms which oxidize sulfur to sulfate with the formation of some thiosulfate.

In an attempt to obtain sodium carbonate, Chaussier in 1799 obtained sodium thiosulfate as a by-product from the reaction of sodium sulfate with charcoal. The constitution was uncertain and, in 1813, Gay Lussac wrongly regarded the salt as the derivative of an acid, intermediate in oxidation between sulfur and sulfurous acid. In consequence, he designated the acid "hyposulfurous acid" and the salt "hyposulfite of soda." This name for the salt has persisted to the present, particularly among photographers, who have shortened it to "hypo." In 1877, von Wagner suggested calling the acid thiosulfuric acid to indicate its relation to sulfuric acid and to distinguish it from other sulfur acids, particularly hydrosulfurous acid, $H_2S_2O_4$. At present the terms thiosulfuric acid and thiosulfates are generally accepted in chemistry.

Properties of Thiosulfuric Acid

On the basis of physical and chemical evidence including experiments with radioactive sulfur, it has been clearly established that the structure of thiosulfuric acid consists in a substitution of one oxygen in sulfuric acid by an atom of sulfur. The salts and ester salts can be considered to be derived from $SO_2(OH)(SH)$.

A dilute solution of thiosulfuric acid can be obtained by treating a solution of the lead salt with hydrogen sulfide or sulfuric acid and filtering off the precipitate, or by adding an equivalent amount of hydrochloric acid to a solution of sodium thiosulfate if there is no objection to the sodium chloride formed at the same time.

Thiosulfuric acid is a relatively strong acid. In measurements of the acidity of different sulfur acids, Kolthoff (16) found thiosulfuric stronger than sulfuric but weaker than hydrosulfurous acid. From pH measurements at 25°C. with a glass electrode Yui and Hagisawa (43) found for the second dissociation constant, $K_2 = 2.73 \times 10^{-2}$. Denney and Monk (7) reported 3.3×10^{-2}, and Page (26) 1.9×10^{-2},

which is probably a better figure. Thiosulfuric acid is a dibasic acid, but only the normal salts are known. Denney and Monk (7) give $\Lambda_0 = 87.4$ for $S_2O_3^{2-}$. The absorption spectra for thiosulfuric acid, sodium thiosulfate, and sodium ethyl thiosulfate have been measured by Lay and König (19). The infrared absorption spectra between 6 and 20μ are given by Lecomte (18). The heat of formation of the thiosulfate ion, $S_2O_3^{2-}$, at a theoretical molality of one is -154.0 kg.-cal./mole at 25°C. and the free energy of formation, -122.7 kg.-cal./mole. Scheffer and Böhm (32) by an indirect method have found that the normal oxidation-reduction potential of solutions of thiosulfate ion, $S_2O_3^{2-}$, and tetrathionate ion, $S_4O_6^{2-}$, in neutral solution is approximately 0.40 volt.

Sodium thiosulfate decomposes in acid solution:

$$Na_2S_2O_3 \underset{OH^-}{\overset{H^+}{\rightleftharpoons}} Na_2SO_3 + S$$

The mechanism of the decomposition is complicated and has been the subject of a number of investigations. Since there is a time interval between the acidification of a thiosulfate solution and the first appearance of a sulfur cloud or opalescence, early investigators regarded this "induction period" as due to a supersaturation with sulfur. The most probable explanation appears to be as follows (31): Some other reactions take place in acid solutions before any turbidity is observed since there is an increase in the iodine titration. Side reactions involving the formation of polythionates occur (see *Thionic acids*). The $S_2O_3^{2-}$ ion is believed to be relatively stable and there is no decomposition of the thiosulfate until a hydrogen-ion concentration of 2.5×10^{-2} is reached. At that point the $HS_2O_3^-$ ion is formed, which rapidly decomposes to liberate sulfur:

$$S_2O_3^{2-} + H^+ \longrightarrow HS_2O_3^- \qquad (1)$$

$$HS_2O_3^- \longrightarrow HSO_3^- + S \qquad (2)$$

A much slower reaction is the formation of some pentathionic acid which takes place if dilute hydrochloric acid is used:

$$6\,H^+ + 5\,S_2O_3^{2-} \longrightarrow 2\,S_5O_6^{2-} + 3\,H_2O \qquad (3)$$

If concentrated hydrochloric acid is used, H_2S and H_2S_2 are formed, presumably from the monatomic sulfur.

Thiosulfuric acid and thiosulfates can be oxidized to sulfates or polythionates according to the conditions.

Analysis of Thiosulfates

Thiosulfates can be detected by a number of reactions. A simple one is the evolution of sulfur dioxide and separation of sulfur when a solution is treated with hydrochloric acid. Precipitates are obtained by the addition of solutions of silver, copper, lead, or barium salts. The silver precipitate is at first white, gradually turning yellow, then brown, and finally black as the sulfide is formed. The change is accelerated by warming. Lead and barium thiosulfates are sparingly soluble. In the case of lead, the precipitate is soluble in excess of thiosulfate and blackens on warming.

Solutions of thiosulfates give a number of color reactions. With ferric chloride solution a transient violet color results. A solution of sodium nitroprusside which has turned brown by exposure to the air gives a blue color. A sensitive test is a blue

"ring test" when a solution of the thiosulfate is carefully poured onto a mixture of ammonium molybdate solution and concentrated sulfuric acid.

Gravimetrically, the total sulfur can, of course, be readily determined as barium sulfate after oxidation by chlorine or other suitable oxidizing agent. Titration with iodine is the commonly used volumetric method of analysis, sodium tetrathionate being formed:

$$2\ Na_2S_2O_3 + I_2 \longrightarrow 2\ NaI + Na_2S_4O_6$$

No change of acidity or alkalinity takes place in this reaction. An alternate method is the oxidation of the thiosulfate with hydrogen peroxide. An initial known quantity of alkali is added and the excess remaining after boiling is measured by titration with acid:

$$Na_2S_2O_3 + 2\ NaOH + 4\ H_2O_2 \longrightarrow 2\ Na_2SO_4 + 5\ H_2O$$

In another procedure, mercuric chloride can be added, which reacts to give a white precipitate of $HgCl_2.2HgS$ and HCl, the reaction being:

$$2\ Na_2S_2O_3 + 3\ HgCl_2 + 2\ H_2O \longrightarrow 2\ Na_2SO_4 + 4\ HCl + HgCl_2.2HgS$$

The amount of thiosulfate can be estimated by titrating the acid formed. The method can be applied in the presence of sulfides, which give a precipitate but develop no acidity. For details of analyses see reference (17).

Sodium Thiosulfate

Sodium thiosulfate (sodium hyposulfite, "antichlor," sodium subsulfite, "hypo"), $Na_2S_2O_3.5H_2O$, formula weight 248.21, is the best-known and most important of the thiosulfates. A good summary of properties, etc., is given in reference (12). When the salt is crystallized from aqueous solution at ordinary temperatures, the pentahydrate is formed as transparent prisms belonging to the monoclinic system. The commercial product occurs as colorless crystals or white granules which are odorless and possess a cooling taste. They are fairly stable under ordinary conditions in air, effloresing in warm dry air and deliquescing slightly in moist air. The aqueous solution is neutral. The product is insoluble in alcohol.

TABLE I. Solubility of α-Pentahydrate in Water.

Solid phase	Temperature, °C.	Solubility, parts of $Na_2S_2O_3$ in 100 parts of water
α-$Na_2S_2O_3.5H_2O$ + ice	−11	42.8
α-$Na_2S_2O_3.5H_2O$	0	50.15
	10	59.66
	20	70.07
	30	82.45
	40	103.37
	48.2 (transition point)	159.78
α-$Na_2S_2O_3.2H_2O$	50	165.11
	60	191.30
	65	212.90
$Na_2S_2O_3.\frac{1}{2}H_2O$	65	214.90
	70	223.20
$Na_2S_2O_3$	70	223.10
	80	231.80

PHYSICAL AND CHEMICAL PROPERTIES

The α-pentahydrate melts in its own water of crystallization at 48.5°C.; d_4^{27} 1.715; n_D^{20} α 1.4886; β 1.5079; γ 1.5360; heat of formation ΔH_0 (α-form), −621.89 kg.-cal./mole; heat of fusion, 11.85 kg.-cal./mole; specific heat (21°C.), 0.346 cal./g.; cryoscopic constant ($K_F = \Delta T/N$), 42.6. The decomposition pressure of the pentahydrate (forming the anhydrous salt) has been published (15). The vapor pressure of a saturated solution at 20°C. is 12 mm. and at 40°C., 33.2 mm.

The α-pentahydrate is the stable form at all temperatures below 48.2°C. If any of the other forms are cooled to about −35°C., they spontaneously start to convert to the α-pentahydrate. The change then proceeds quite rapidly as the mixture is warmed to room temperature.

Young and Burke (42) have described thirteen crystalline modifications of sodium thiosulfate: one hexahydrate, two pentahydrates, one tetrahydrate, two di-

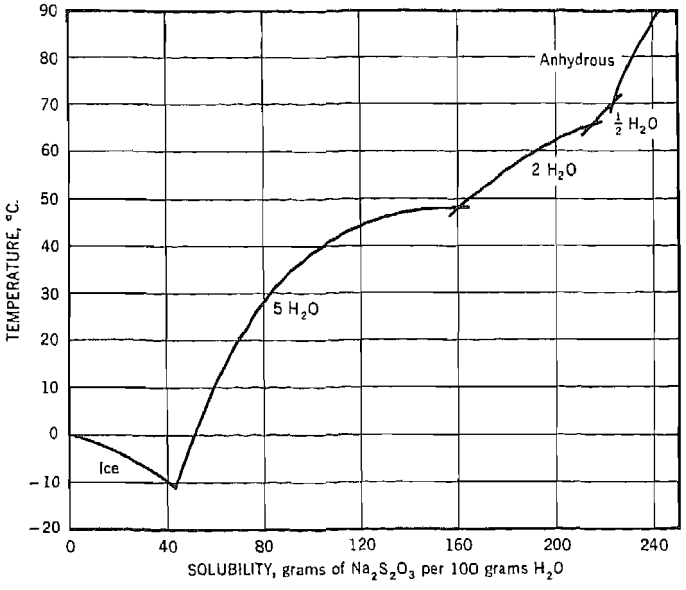


Fig. 1. Solubility of sodium thiosulfate in water.

hydrates, one sesquihydrate, one four-thirds-hydrate, three monohydrates, one hemihydrate, and an anhydrous form. The solubility in water of the stable forms is shown in Table I and Figure 1. Solutions of sodium thiosulfate readily supercool considerably below their normal crystallization points.

The boiling points of aqueous solutions have been determined by Gerlach (11).

The density of solutions is as follows (14):

$Na_2S_2O_3$, %	10	30	40
d_4^{20}	1.0827	1.2739	1.3827

The surface tension at 40°C. has been measured by Livingston, Morgan, and Schramm (20).

Data on the electrical conductance of aqueous solutions at different temperatures have been given by Watkins and Jones (41).

Typical inorganic reactions of sodium thiosulfate are given in Table II.

TABLE II. Typical Inorganic Reactions of Sodium Thiosulfate.

Reactants and conditions	Products
Heating to 300°C	Na_2SO_4, Na_2S_5
Strong heating in absence of air	Na_2SO_4, Na_2S, S
Heating in air, slow oxidation	Na_2SO_4, SO_2, H_2O
Heat plus reducing agent (H_2, C, or S)	Na_2S, corresponding sulfide
"Nascent" H, aqueous solution	Na_2S, H_2S, H_2O
Electrolysis of aqueous solution	$S_4O_6^{2-}$
I_2, aqueous solution	$Na_2S_4O_6$, NaI
Br_2, aqueous solution	$NaHSO_4$, HBr, ($Na_2S_4O_6$)
Cl_2, aqueous solution	$NaHSO_4$, HCl, ($Na_2S_4O_6$)
NaOCl, acid or $NaHCO_3$ solution	$NaHSO_4$, HCl
NaOCl, dilute solution	Na_2SO_4, $Na_2S_4O_6$, NaCl
HNO_3 or $KMnO_4$, solution	H_2SO_4 or $NaHSO_4$
$NaNO_3$, dry heat	May explode
HIO_3 or $FeCl_3$, solution	$Na_2S_4O_6$ and/or $Na_2S_2O_8$
H_2O_2, alkaline solution	$Na_2S_4O_6$, Na_2SO_4
H_2O_2, acetic acid solution	$Na_2S_4O_6$
HCl, aqueous solution	SO_2, S, NaCl
NH_4Cl, boiling solution	NH_3, SO_2, S
Na amalgam, aqueous solution	Na_2SO_3, Na_2S
Finely divided Cu, boiling solution	CuS, Na_2SO_3

MANUFACTURE

It is possible to prepare sodium thiosulfate, of varying degrees of purity, by a number of methods—many involving the use of by-products from the manufacture of other materials. Of particular historical interest is the process formerly used for the recovery of thiosulfate from the alkali waste of the Leblanc soda process (see Vol. **1**, p. 386) by atmospheric oxidation of this material in the presence of sodium sulfate. The purity of the product was stated to be 98% $Na_2S_2O_3.5H_2O$. In place of sodium sulfate, the more expensive carbonate was sometimes used. The reactions were as follows:

$$Ca(SH)_2 + 2\,O_2 \longrightarrow CaS_2O_3 + H_2O$$

$$CaS_2O_3 + Na_2SO_4 \longrightarrow Na_2S_2O_3 + CaSO_4$$

The process offered a means of disposing of a highly objectionable waste and at the same time utilized a cheap and easy process. Until the Leblanc soda process was supplanted by the Solvay ammonia process, the alkali waste of the former represented essentially the only commercial source of "hypo" (21).

A source of sodium thiosulfate today is from the waste sulfur liquor obtained in the manufacture of sulfur black and other sulfur dyes (*q.v.*). In these processes organic nitro compounds are boiled with a solution of sodium polysulfide which is almost completely converted to thiosulfate. Since the dyes are insoluble, they can be separated by filtration. The filtrate is purified with activated carbon and the thiosulfate obtained by concentration and crystallization. The product is stated to contain about 96% $Na_2S_2O_3.5H_2O$ (10,25).

Another method of preparation is from sodium sulfide. Sulfur dioxide is passed into a dilute solution of sodium sulfide and sodium carbonate (not over 10% of each), and the following reaction takes place:

$$Na_2CO_3 + 2\,Na_2S + 4\,SO_2 \longrightarrow 3\,Na_2S_2O_3 + CO_2$$

A German modification of this is to treat the mother liquor from sodium sulfide crystallization with sulfur dioxide until the mixture is just acid. An excess of sulfurous acid forms polythionic acids. The solution is neutralized with some sodium sulfide, clarified, filtered, evaporated to 50–52°Bé. (approximately 800 grams $Na_2S_2O_3$ per liter), and transferred to crystallizers. The crystals are centrifuged and dried at 30–40°C. to give transparent colorless crystals analyzing 98% $Na_2S_2O_3.5H_2O$ (10,34,25). The reaction is:

$$2\ Na_2S + 3\ SO_2 \longrightarrow 2\ Na_2S_2O_3 + S$$

If hydrogen sulfide is treated at 20–40°C. with a mixture of equimolecular parts of sodium sulfite and sodium acid sulfite, the following reaction can be carried out:

$$2\ Na_2SO_3 + 2\ NaHSO_3 + 2\ H_2S \longrightarrow 3\ Na_2S_2O_3 + 3\ H_2O$$

The yield is 95–96%. At higher temperatures the yield is decreased, or if the reagents vary more than 10% from the theory a serious drop in yield of thiosulfate occurs. The mother liquor is recycled (44). *NaHS and $NaHSO_3$ may be used in a similar* reaction which has been commercially applied.

Sodium thiosulfate can be obtained from spent iron oxide resulting from the purification of coal gas. (See Vol. **3**, p. 168.) The oxide is treated with hot caustic soda solution and the polysulfides so formed are oxidized, preferably by passing air through the solution countercurrently at or near the boilint point:

$$Na_2S_x + O_2 \longrightarrow Na_2S_2O_3$$

Modifications utilize a solution of sodium sulfite or sodium carbonate and sulfur dioxide (46).

An important commercial process is based on the reaction between sodium sulfite and sulfur:

$$Na_2SO_3 + S \longrightarrow Na_2S_2O_3$$

A slurry of sodium sulfite, prepared by treating soda ash with sulfur dioxide, is digested with an excess of sulfur until all sulfite is converted to thiosulfate. The thiosulfate liquor is filtered, concentrated, and crystallized, the crystal slurry is centrifuged, mother liquor being recycled, and the crystals are then dried, screened, and packaged. Plain steel equipment is commonly used although steel alloys, Monel, glass, porcelain, stoneware, and Haveg may be used if a completely iron-free product is required (34,37,13,10).

Duriron, Hastelloy, Stellite, and most stainless alloy steels are suitable for handling sodium thiosulfate solutions. Lead is recommended for general photographic use. Monel, glass, porcelain, stoneware, and Haveg are completely resistant. Monel and nickel show slight attack in boiling concentrated solutions. Cast iron or plain steel should be avoided if iron contamination is not permissible (27).

Anhydrous sodium thiosulfate can be readily obtained by dehydration of a hydrate at a temperature not exceeding 105°C. or by crystallizing from solution at a temperature above 70°C.

As of 1954, there are five manufacturers of sodium thiosulfate in the U.S. and one in Canada. According to the Bureau of the Census, the U.S. production in 1953, in terms of $Na_2S_2O_3.5H_2O$, was approximately 36,534 short tons.

Prices of crystal sodium thiosulfate, $Na_2S_2O_3.5H_2O$, as of May, 1954, ranged from about five cents a pound upward, depending on the type of package, shipping point,

and quantity involved. Prices for the anhydrous salt ranged from about seven cents a pound upward under the same conditions.

ANALYSIS AND SPECIFICATIONS

The thiosulfate content is determined by titration with standard iodine solution. The test for sulfate and sulfite consists in adding an excess of iodine solution and comparing the turbidity produced by the addition of barium chloride in hydrochloric acid solution to that produced from a known quantity of sulfate. The test for sulfide consists in adding a definite quantity of alkaline lead acetate which should produce no dark color within one minute (limit is about 0.0002% as S). While not specified, the reagent grade product should have at least 99% purity.

Specifications for different grades are given in Tables III–V.

TABLE III. Specifications for A.C.S. Reagent and U.S.P. Grades.

Specifications	A.C.S. reagent grade (29)	U.S.P. grade (40)
Insoluble matter	Not more than 0.005%	Not more than 0.005%
Sulfate and sulfite (as SO_4)	Not more than 0.10%	Not more than 0.10%
Sulfide (as S)	To pass test	To pass test
Neutrality[a]	Max. 0.05 ml., 0.1 *N* alkalinity	No alkalinity
	Max. 0.05 ml., 0.1 *N* acidity	Max. 0.05 ml., 0.1 *N* acidity

[a] 5 g. in 50 ml. CO_2-free H_2O, test to phenolphthalein end point.

TABLE IV. U.S. Federal Specification, Sodium Thiosulfate, Photographic (38).

Specification	Type I—crystalline ($Na_2S_2O_3.5H_2O$)[a]	Type II—anhydrous ($Na_2S_2O_3$)
Assay	Not less than 99.0% as $Na_2S_2O_3.5H_2O$	Not less than 97.0% as $Na_2S_2O_3$
Neutrality	Not to exceed 0.016% as NaOH	Not to exceed 0.056% as NaOH
	Not to exceed 0.010% as H_2SO_4	Not to exceed 0.010% as H_2SO_4
Sulfide	Not to exceed 0.001% as Na_2S	Not to exceed 0.002% as Na_2S
Insoluble matter and calcium and magnesium, and material precipitated by ammonium hydroxide	Not to exceed 0.2%	Not to exceed 0.4%
Heavy metals	Not to exceed 0.001% as Pb	Not to exceed 0.002% as Pb
Iron	Not to exceed 0.005%	Not to exceed 0.008%
Appearance of solution	Clear and free from sediment or undissolved solids. A slight flocculence may be disregarded.	

[a] Class 1—granular crystals, class 2—rice crystals or prismatic.

TABLE V. U.S. Federal Specification, Sodium Thiosulfate (Hyposulfite), Technical (39).

Specification	Grade A, granular	Grade B, pea crystals
Assay	Not less than 98.5% as $Na_2S_2O_3.5H_2O$	Not less than 97.0% as $Na_2S_2O_3.5H_2O$
Insoluble matter	Not to exceed 0.025%	Not to exceed 0.025%
Neutrality[a]	Max. alkalinity equivalent to 3 drops 0.1 *N* acid	Max. alkalinity equivalent to 3 drops 0.1 *N* acid
	Max. acidity equivalent to 1 drop 0.1 *N* alkali	Max. acidity equivalent to 1 drop 0.1 *N* alkali

[a] 5 g. in 50 ml. CO_2-free H_2O, test to phenolphthalein end point.

USES

It is estimated that the end-use distribution of sodium thiosulfate was as shown in Table VI.

TABLE VI. End-Use Distribution.

Photography	60%
Leather	18%
Tetraethyl lead	7%
Thioglycolic acid	3.5%
Paper and textiles	2.5%
Miscellaneous including chemical and analytical	6%
Export	3%
Total	100.0%

Thiosulfates are practically universally used in fixing baths in photography (*q.v.*) because of their ability to dissolve the unreduced silver bromide left in the developed negative or print as soluble complex thiosulfatoargentates(I). The equation is:

$$3\ AgBr + 4\ Na_2S_2O_3 \longrightarrow Na_5[Ag_3(S_2O_3)_4] + 3\ NaBr$$

Since the developing solution is alkaline and a certain amount is carried over into the fixing bath, a weak acid (for example, acetic) is added to the latter for neutralization. To prevent decomposition of the thiosulfate, a small amount of sodium sulfite is added and a hardening agent for the gelatin such as potassium alum. Thus a typical fixing solution may contain 20–30% of its weight of hypo, 3% of 28% acetic acid, 1% of anhydrous sodium sulfite, and 1% of potassium alum. If the chemicals of the fixing bath, particularly the hypo, are left in the negative or print, discoloration or fading (due essentially to the formation of silver sulfide) takes place on aging so their complete removal by thorough washing is important. To hasten this operation the use of neutralizing agents, such as dilute ammonia, has been recommended. These convert the thiosulfate to more easily removed salts.

Solutions of sodium thiosulfate are utilized in practically every analytical chemical laboratory. However, the lack of stability over a period of time is one of their main drawbacks. The U.S. Dispensatory states that 0.1 *N* and 0.01 *N* solutions should be frequently restandardized, 0.005 *N* solutions should not be used if prepared more than seven days beforehand, and 0.0001 *N* solutions should be prepared on the day of use. This lack of stability has been the subject of much study. The decomposition is due to several causes, the most important being the action of thiobacteria. Small amounts of carbon dioxide in the air dissolve to give a slight acidity which accelerates the formation of sulfur. A third agent is the absorption of oxygen from the air.

In preparing standard thiosulfate solutions, it is recommended that the water, salt, and container be sterile. The water should be freshly distilled and the stock solution stored preferably in full, well-stoppered bottles in a cool, dark place. The addition of inhibitors, such as mercuric iodide (10 mg./l.), amyl alcohol (1% by volume), chloroform (1 ml./l.), sodium benzoate (0.1%), and mercuric cyanides (0.1 g./l.), has been suggested. It has been claimed by Ehrlich (9) that the addition of 0.05% sodium hydroxide and 0.1% sodium benzoate will maintain 0.1 *N* $Na_2S_2O_3$ unchanged for five months. However, of several inhibitors tested, mercuric iodide and chloroform were found to be the most satisfactory by Rue (30), though they were

only effective for about two months at 40°C. The pure anhydrous salt dried at 120°C. can be used as a primary analytical standard.

Sodium thiosulfate is used in chrome leather manufacture where it is used to reduce the dichromate to chrome alum (36). (See Vol. 8, p. 299.) It can also be used as an antichlor to neutralize the residual chlorine in textiles and paper; for the extraction of silver from ores; in gold and silver plating baths; as a mordant for dyeing and printing of textiles; as a bleach for straw, wool, ivory, and oils; in the preparation of silvering solutions; as a preservative against fermentation; to prevent the yellowing of soap on aging; in cosmetic preparations; and in chemical syntheties. For the use of sodium thiosulfate in the manufacture of tetraethyl lead see U.S. Patent 2,513,659 (52), and Vol. 8, p. 277.

A recent use has developed in the manufacture of thioglycolic acid (*q.v.*) for applications in hair preparations as a wave-set. Presumably the thiosulfate is treated with sodium chloroacetate to give a Bunte salt (see p. 113):

$$NaOOCCH_2Cl + Na_2S_2O_3 \longrightarrow NaOOCCH_2SSO_3Na + NaCl$$

This is easily hydrolyzed with mineral acid to give thioglycolic acid:

$$NaOOCCH_2SSO_3Na + H_2O + H_2SO_4 \longrightarrow HOOCCH_2SH + 2\,NaHSO_4$$

See Vol. **12**, p. 239.

The application of sodium thiosulfate in medicine has been extensively studied from early days. Originally it was believed that in contact with the skin it would liberate the sulfide ion and exert the parasiticidal effect of the sulfides. In only a few cases has it proved effective. Its use in swimming pools as a footbath in the form of a 10% solution as a preventive of ringworm infection of the feet has been reported to have given excellent results. It has been recommended for the treatment of arsenical dermatitis resulting from the use of arsphenamine. Although it is of questionable value as an antidote for arsenic, lead, and mercury poisoning, it has been found useful as an internal antidote for poisoning by cyanides with which it forms a relatively nontoxic thiocyanate, and as an antidote for iodine poisoning. Favorable results have been reported from internal use in the treatment of nonarsenical skin diseases, especially eczema and urticaria. In veterinary use, it is an old remedy for tympanitis in horses and cattle. Externally it has been used in the treatment of ringworm and mange. Alternate treatments of a saturated sodium thiosulfate solution and 1–5% hydrochloric acid have been found effective against fleas, lice, and sarcoptic mange.

The use of anhydrous sodium thiosulfate as a substitute for the pentahydrate is rapidly increasing. It has the advantages of a saving of about 36% in weight and even more in bulk and has a better shelf-life in ready-mixed photographic preparations. It is, however, hygroscopic.

Ammonium Thiosulfate

Ammonium thiosulfate ("ammonia hypo"), $(NH_4)_2S_2O_3$, formula weight 148.21, is becoming an important technical salt. It occurs as anhydrous, colorless, or white tabular crystals, d_4^{23} 1.641, belonging to the monoclinic system. The solubility in water is 173 g./100 g. water at 20°C., 205 at 40°C., and 269 at 80°C. It is deliquescent in air and somewhat unstable unless kept under an atmosphere of ammonia. It is insoluble in ether and alcohol. On heating to 150°C., it sublimes with some decomposition into ammonium sulfite, sulfur, water, ammonia, and hydrogen sulfide.

Manufacture. Ammonium thiosulfate is produced by the reaction of a concentrated solution of ammonium sulfite with ammonium polysulfide in the presence of an excess of ammonia at 30–55°C. Ammonium bisulfite can be added if desired. The reaction is:

$$(NH_4)_2SO_3 + (NH_4)_2S_x \longrightarrow (NH_4)_2S_2O_3 + (NH_4)_2S_{x-1}$$

The solution is filtered to remove small amounts of sulfur, an additional amount of ammonium hydroxide is added, and the solution is evaporated either under vacuum at low temperature, or in the presence of ammonia and ammonium sulfite in stainless steel equipment. The crystals are separated and dried in an atmosphere containing ammonia at about 50°C. The final product is stored in gastight containers under an atmosphere of ammonia (49,50,51,53).

Other methods of obtaining it include the reaction of ammonium carbonate with calcium thiosulfate:

$$(NH_4)_2CO_3 + CaS_2O_3 \longrightarrow (NH_4)_2S_2O_3 + CaCO_3$$

and the recovery as a by-product in the reduction of *p*-dinitrobenzene to *p*-nitroaniline by means of ammonium sulfide.

In May 1954, there were three manufacturers of ammonium thiosulfate in the U.S. Price of a 60% solution ranged from about eight cents a pound upward depending on the type of container, shipping point, and quantity involved.

Specifications. The product is marketed either in the form of colorless or white glistening crystals, or in the form of a 60% aqueous solution. The U.S. Military Specifications for ammonium thiosulfate (for photographic use), MIL-A-1327, 3 August 1949 as regards purity are shown in Table VII.

TABLE VII. MIL Specification for Ammonium Thiosulfate, Photographic.

Assay	Not less than 97% $(NH_4)_2S_2O_3$
$(NH_4)_2SO_3$	Not to exceed 2.0%
Heavy metals	Less than 0.002%
Insoluble in water	Not to exceed 0.1% (soln. shall be clear and free from precipitates of any kind)
Water or water vapor	Not more than 1%
pH (30 g. dissolved in 20 g. boiled distilled water)	Not less than 6.0 and not greater than 8.0
Sulfides	Free from sulfides
Sulfur	No free sulfur

Uses. While ammonium thiosulfate has been recommended for use in iodometry and as a metal-cleaning agent, the main interest in it lies in the fact that it reacts considerably faster than sodium thiosulfate in photographic fixing baths. For light work it reacts approximately twice as fast and for heavy work approximately four times as fast. It has about twice the life of the sodium solution, that is, it can be used about twice as long before discarding. A somewhat shorter washing period is required. The recovery of dissolved silver salts from used solutions is simplified as the ammonium salts can be volatilized on heating.

Other Metal Thiosulfates

Many of the simple neutral inorganic salts of thiosulfuric acid have been prepared but outside of the sodium, ammonium, calcium, and barium salts, they are of com-

paratively little technical interest. Except for the thallous, silver, lead, and barium salts which are sparingly soluble, they are moderately or very soluble in water. The ammonium, lead, and silver salts are anhydrous, but many of the others form more than one hydrate. The products are odorless, well-defined crystals which are relatively stable at room temperature. Aqueous solutions are generally stable in the cold and in the absence of air. Chemically they show the normal reactions of the thiosulfate radical and the respective cation.

The thiosulfates are formed by treating a solution of calcium or barium thiosulfate with the carbonate or sulfate of the desired metal. The calcium or barium carbonate or sulfate, which precipitates, can be filtered off and the desired thiosulfate crystallized from the filtrate. An alternate method is to mix a concentrated solution of sodium thiosulfate with the chloride of the desired metal and separate the sodium chloride from the desired thiosulfate by fractional crystallization (5).

Calcium Thiosulfate. Calcium thiosulfate (calcium hyposulfite), $CaS_2O_3.6H_2O$, formula weight 260.31, occurs in the form of triclinic crystals, d_4^{16} 1.873, refractive index 1.56. The solubility in water is 34.7 at 0°C., 49.4 at 20°, and 67.9 at 40° (expressed in grams of anhydrous salt per 100 grams of water) the solid phase being $CaS_2O_3.6H_2O$ (45). It is insoluble in alcohol. At a temperature of 18°C., it is stable under a vapor pressure of water of 9–12 mm., but when heated to 30°C. it loses 5 moles of water. The free energy of formation of the hexahydrate is −602.2 kg.-cal./mole. On heating a solution to 60°C., decomposition starts with the separation of sulfur. The specific heat and free energy of solutions of calcium thiosulfate, as well as the heat of reaction and free energy change for the reaction:

$$S \text{ (rhombic)} + CaSO_3.2H_2O \longrightarrow CaS_2O_3\,(M) + 2\,H_2O$$

have been given by Bichowsky (3).

Calcium thiosulfate can be prepared by heating a suspension of calcium sulfite and sulfur in water to 30–40°C., or by boiling a solution of calcium hydroxide with sulfur and passing in sulfur dioxide until the liquid is decolorized, followed by evaporation below 60°C. It can also be obtained by reducing calcium sulfate by sulfur; or by mixing concentrated solutions of sodium thiosulfate with calcium chloride, removing the sodium chloride first formed, concentrating at about 50°C., and allowing to crystallize at a lower temperature. It is formed as an intermediate product in the oxidation of the alkali waste of the Leblanc soda process (see above), as an intermediate product in lime-sulfur sprays, and in the sulfite liquor of the wood-pulp industry.

Calcium thiosulfate has been employed in the treatment of dermatitis and jaundice resulting from arsphenamine.

Barium Thiosulfate. Barium thiosulfate (barium hyposulfite), $BaS_2O_3.H_2O$, formula weight 267.51, is obtained as brilliant, white, crystalline plates of the rhombic system, d_4^{16} 3.446. The solubility in water at 25°C. is 0.01135 molal (7). It is insoluble in alcohol. On heating to above 100°C. it becomes anhydrous. Heated to a red heat it decomposes:

$$6\,BaS_2O_3 \longrightarrow BaS + 2\,BaSO_3 + 3\,BaSO_4 + 6\,S$$

Barium thiosulfate is easily made by mixing hot, concentrated solutions of sodium thiosulfate and barium chloride or barium acetate and allowing the mixture to cool. It has been used in the manufacture of explosives, matches, luminous paints, and as a convenient raw material for the preparation of other thiosulfates. The hydrate dried at 25–30°C. has been recommended as a primary standard in iodine titrations.

Complex Thiosulfates

The thiosulfates form numerous complex salts of several different types. It has been reported that there can be, at least in the solid state, two potassium sodium thiosulfates, $KOSO_2SNa.2H_2O$ and $NaOSO_2SK.2H_2O$. These melt at 57° and 62°C., respectively, have densities of 1.970 and 1.930, and solubilities of 213.7 and 205.3 parts per 100 parts of water at 15°C. Proof of the structures lay in the reaction with ethyl bromide which in one case gave $KOSO_2SC_2H_5$ and in the other, $NaOSO_2SC_2H_5$ (33).

Examples of double salts are: $K_2S_2O_3.NaCl$, $(N_2H_4)_2.H_2S_2O_3.Cu_2S_2O_3.\frac{1}{2}H_2O$, $Na_2S_2O_3.Cu_2S_2O_3.2NH_3$ (from the action of gaseous ammonia on $Na_2S_2O_3.Cu_2S_2O_3.2H_2O$), and $NaNO_3.Na_2S_2O_3.CaS_2O_3.11H_2O$. These complex salts are generally formed by crystallization from solutions of the individual salts under proper conditions. For further information, reference should be made to Mellor (24).

The silver and gold coordination complexes are of special interest and have been studied fairly extensively. The series of *thiosulfatoargenates*(I) (argentothiosulfates) are of importance in photographic reactions. Mees (23) lists the various sodium thiosulfatoargenates(I) for which there is apparently reliable evidence. Probably all these compounds exist as hydrates. It is doubtful, however, whether all the corresponding anions exist in solution. Some of the salts and their solubilities are: $Na[AgS_2O_3]$, slightly soluble; $Na_6[Ag_4(S_2O_3)_5]$; $Na_5[Ag_3(S_2O_3)_4]$, easily soluble; $Na_4[Ag_2(S_2O_3)_3]$, easily soluble; $Na_3[Ag(S_2O_3)_2]$. Bassett and Lemon (1) have given the results of their study of the system $Na_2S_2O_3$–$Ag_2S_2O_3$–H_2O in the form of a phase diagram.

Sodium thiosulfatoaurate(I) (sodium aurothiosulfate, gold sodium thiosulfate), N.F. IX, $Na_3[Au(S_2O_3)_2].2H_2O$, has long been known, but only since 1924, when it was introduced under the name Sanocrysin for the treatment of tuberculosis, has it been of considerable interest. It is prepared by adding auric chloride to a concentrated solution of sodium thiosulfate. The gold is reduced to the aurous state in this process, after which the complex is precipitated with alcohol. The product is in the form of white glistening crystals, needle-like or prismatic, which are soluble in water but insoluble in alcohol. It has proved effective in the treatment of rheumatoid arthritis and lupus erythematosus.

Esters

O-Esters of thiosulfuric acid are not known. *S*-Esters are known as their ester salts. Sodium ethyl thiosulfate, $C_2H_5SSO_2ONa$, is known as *Bunte's salt*, after its discoverer. Bunte-type salts, RCH_2SSO_2OM, generally form beautiful crystals which are soluble in water and alcohol but insoluble in ether. The free alkyl or aryl thiosulfuric acids are not stable.

Mineral acids generally hydrolyze the alkali metal salts of thiosulfuric esters into a mercaptan (thiol) and the hydrogen sulfate:

$$RCH_2SSO_2ONa + H_2O \longrightarrow RCH_2SH + NaHSO_4$$

This is a commonly used laboratory procedure for preparing thiols and is used commercially for preparing thioglycolic acid (see p. 110). If chlorine is present a sulfonyl chloride is formed:

$$RCH_2SSO_2ONa + 3\,Cl_2 + 3\,H_2O \longrightarrow RCH_2SO_2Cl + NaHSO_4 + 5\,HCl$$

Salts of monoalkyl thiosulfate esters are formed by the reaction of a saturated primary alkyl halide with a thiosulfate:

$$RCH_2Cl + NaSSO_2ONa \longrightarrow RCH_2SSO_2ONa + NaCl$$

Bunte's salt is also formed, although in low yields, when iodine acts on a mixture of the sodium mercaptide and sodium sulfite:

$$C_2H_5SNa + NaSO_3Na + I_2 \longrightarrow C_2H_5SSO_3Na + 2\,NaI$$

Numerous variations of the Bunte salt reaction have been described. For example, sodium thiosulfate can be reacted with halogenated fatty acids that have previously been esterified with saturated or unsaturated aliphatic, hydroaromatic, or aliphatic-aromatic alcohols containing at least six carbon atoms (48), for example:

$$C_{12}H_{25}OOCCH_2Cl + Na_2S_2O_3 \longrightarrow C_{12}H_{25}OOCCH_2SSO_3Na + NaCl$$

The products are claimed to have soap-like properties.

Other compounds are based on condensations of such raw materials as lauryl chloromethyl ether to give wetting or penetrating agents suitable for use in acid wool dye-baths (47). Substituted benzyl chlorides can be condensed to give the respective sodium thiosulfate esters (35). Sodium thiosulfate is used in chrome leather manufacture to reduce the dichromate to trivalent chromium (36).

It is possible to prepare other types of thiosulfate esters. For example, Mazover (22) treated $BrCH_2CH_2CH_2Cl$ with $Na_2S_2O_3$ to give $CH_2(CH_2S_2O_3Na)_2$.

The sodium and potassium salts of phenyl thiosulfate have been prepared (2). The pyridine salt of phenyl thiosulfate is readily obtained in practically quantitative yield by sulfation of thiophenol with pyridine–sulfur trioxide:

$$C_6H_5SH + C_5H_5N.SO_3 \longrightarrow C_6H_5S_2O_3(C_5H_5NH)$$

The pyridine salt can be readily converted to the sodium or potassium salt by reaction with sodium or potassium ethylate in alcohol. The potassium, diethylamine, and aniline salts of 2-naphthyl thiosulfate and the potassium salt of 1-anthraquinonyl thiosulfate have been prepared in a similar manner (8).

Del Pianto (6) has reported favorably on the use of a mixture of sodium ethyl thiosulfate and sodium mercaptobenzothiazole-5-sulfonic acid in the prevention and treatment of tuberculosis, although neither compound alone showed much action.

Salts of amines with thiosulfuric acid have been prepared and have been referred to as esters. Cyclohexylamine thiosulfate has been prepared by treating *N*-methylenecyclohexylamine in ethyl alcohol with hydrogen sulfide (4). An alternate method is to saturate cyclohexylamine in ethyl alcohol with hydrogen sulfide and oxidize the mixture with air. Morpholine thiosulfate was obtained by allowing morpholine to stand in contact with sulfur and air at room temperature for three weeks (28).

Bibliography

(1) Bassett, H., and Lemon, J. T., *J. Chem. Soc.*, **1933**, 1423.
(2) Baumgarten, P., *Ber.*, **B63**, 1330–5 (1930).
(3) Bichowsky, F. R., *J. Am. Chem. Soc.*, **45**, 2225–35 (1923).
(4) Braithwaite, E. R., and Graymore, J., *J. Chem. Soc.*, **1950**, 208–10.
(5) Carlsohn, H., and Werner, F., *Z. anorg. Chem.*, **197**, 167–81 (1931).
(6) Del Pianto, E., *Ricerca sci.*, **20**, 83–101 (1950).
(7) Denney, T. O., and Monk, C. B., *Trans. Faraday Soc.*, **47**, 992–98 (1951).
(8) Dornow, A., *Ber.*, **B72**, 568–70 (1939).
(9) Ehrlich, J., *Ind. Eng. Chem., Anal. Ed.*, **14**, 406 (1942).
(10) Faith, W. L., Keyes, D. B., and Clark, R. L., *Industrial Chemicals*, Wiley, N.Y., 1950, pp. 579–82.

(11) Gerlach, G. T., *Zeit. anal. Chem.*, **26**, 436 (1887).
(12) Gmelin, 8th ed., 1928, System-Nummer 21, pp. 602–23.
(13) Hargreaves, L., and Dunningham, A. C., *J. Soc. Chem. Ind. (London)*, **42**, 147–52T (1923).
(14) I.C.T., Vol. III, p. 81.
(15) I.C.T., Vol. VII, p. 305.
(16) Kolthoff, I. M., *Rec. trav. chim.*, **43**, 216–20 (1924).
(17) Kurtenacker, A., *Analytische Chemie der Sauerstoffsäuren des Schwefels*, F. Enke, Stuttgart, 1938, pp. 105–34.
(18) Lecomte, J., *Cahiers phys.*, **17**, 1–26 (1943).
(19) Ley, H., and König, E., *Z. physik. Chem.*, **B41**, 365–87 (1938).
(20) Livingston, J., Morgan, R., and Schramm, E., *J. Am. Chem. Soc.*, **35**, 1851 (1913).
(21) Lunge, G., *The Manufacture of Sulphuric Acid and Alkali*, 3rd ed., Van Nostrand, N.Y., 1909, Vol. II, Pt. II, p. 988.
(22) Mazover, Y. G., *Zhur. Obshchei Khim.*, **19**, 843–8 (1949).
(23) Mees, C. E. K., *Theory of the Photographic Process*, Macmillan, N.Y., 1942, p. 512.
(24) Mellor, 1930, Vol. X, pp. 514–563.
(25) Neumann, B., *Lehrbuch der Chemischen Technologie und Metallurgie*, Springer, Berlin, 1939, Vol. 1, p. 393.
(26) Page, F. M., *J. Chem. Soc.*, **1953**, 1719–24.
(27) Perry, *Chemical Engineers' Handbook*, 3rd ed., McGraw-Hill, N.Y., 1950, p. 1518.
(28) Peters, E. M., and Smith, W. T., Jr., *Proc. Iowa Acad. Sci.*, **57**, 211–13 (1950).
(29) Reagent Chemicals, American Chemical Society Specifications, American Chemical Society, Washington, D.C., 1950, p. 360.
(30) Rue, S. O., *Ind. Eng. Chem., Anal. Ed.*, **14**, 802–5 (1942).
(31) Scheffer, J., and Böhm, F., *Z. anorg. Chem.*, **183**, 151–88 (1929).
(32) Scheffer, J., and Böhm, F., *Z. Elektrochem.*, **35**, 484–86 (1929).
(33) Schwicker, A., *Ber.*, **22**, 1733–34 (1889).
(34) Shreve, R. N., *The Chemical Process Industries*, McGraw-Hill, N.Y., 1945, p. 267.
(35) Speroni, G., and Mannelli, G., *Gazz. chim. ital.*, **70**, 472–78 (1940).
(36) Stiasny, E., and Prakke, F., *Collegium*, **1933**, 465–94.
(37) Uhthoff, J., *Quimica e industria*, **7**, 85–90 (1930).
(38) U.S. Federal Specification, O-S-616,b (Feb. 26, 1954).
(39) U.S. Federal Specifications O-S-616 (Dec. 15, 1941, amended July 28, 1942).
(40) U.S.P. XIV, p. 916.
(41) Watkins, C., and Jones, H. C., *J. Am. Chem. Soc.*, **37**, 2628 (1915).
(42) Young, S. W., and Burke, W. E., *J. Am. Chem. Soc.*, **26**, 1413–22 (1904); **28**, 315–47 (1906).
(43) Yui, N., and Hagisawa, H., *Bull. Inst. Phys. Chem. Research (Tokio)*, **21**, 597–600 (1942).
(44) Zil'berman, Ya. I., and Fridman, V. M., *Zhur. Priklad. Khim.*, **19**, 55–62 (1946).
(45) Zil'berman, Ya. I., and Ivanov, P., *Zhur. Obshchei Khim.*, **16**, 1589–98 (1946).
(46) Australian Pat. 116,972 (May 27, 1943), G. C. McKillop (to Kodak Australasia Proprietary, Limited).
(47) Ger. Pat. 578,568 (June 15, 1933), Deutsche Hydrierwerke A.-G.
(48) U.S. Pat. 2,004,873 (June 11, 1935), A. Kirstahler and W. J. Kaiser; Ger. Pat. 636,260 (Oct. 15, 1936), A. Kirstahler and W. J. Kaiser (to Henkel & Cie, G.m.b.H.).
(49) U.S. Pat. 2,219,258 (Oct. 22, 1940), W. H. Hill (to American Cyanamid Co.).
(50) U.S. Pat. 2,315,534 (April 6, 1943), M. Marasco (to du Pont).
(51) U.S. Pat. 2,412,607 (Dec. 17, 1946), H. V. Farr and J. R. Ruhoff (to Mallinckrodt Chemical Works).
(52) U.S. Pat. 2,513,659 (July 4, 1950), H. J. Madden (to Ethyl Corp.).
(53) U.S. Pat. 2,586,459 (Feb. 19, 1952), H. V. Farr and J. R. Ruhoff (to Mallinckrodt Chemical Works).

R. V. TOWNEND

2-THIOURACIL, $NH.CS.NH.CO.CH:CH$. See "Antithyroid substances" under *Thyroid and antithyroid preparations.*

THIOUREA, NH_2CSNH_2. See *Amino resins and plastics*, Vol. **1**, pp. 744, 749; *Urea (derivatives).*

THIURAM SULFIDES. See "Accelerators of vulcanization" under *Rubber chemicals.*

THIXOTROPY. See *Colloids*, Vol. **4**, p. 239; *Rheology*, Vol. **11**, p. 741.

THIYL RADICALS, RS· See *Sulfides, organic*, Vol. **13**, p. 295.

THOMSONITE, $NaCa_2(Al_5Si_5O_{20}).6H_2O$. See *Silica and silicates (mineral)*, Vol. **12**, p. 279.

THONZYLAMINE HYDROCHLORIDE, $C_4H_3N_2N(CH_2C_6H_4OCH_3)CH_2CH_2N(CH_3)_2.HCl$. See *Histamine and antihistamine agents*, Vol. **7**, p. 472.

THORIATED TUNGSTEN. See *Vacuum tubes.*

THORITE, $ThSiO_4$. See *Silica and silicates (mineral)*, Vol. **12**, p. 279.

THORIUM AND THORIUM COMPOUNDS

Thorium, atomic number 90, atomic weight 232.05, is the second element in the actinide series of the elements (the second rare-earth-like series beginning with actinium). It is one of the naturally occurring radioactive elements and is the parent of the thorium disintegration series (see *Radioactive elements, natural*, Vol. **11**, p. 438). Although the natural occurrence of seven isotopes of thorium has been demonstrated (masses 227, 228, 229, 230, 231, 232, and 234) and that of an eighth (mass 235) has been inferred, Th^{232} is the commonly occurring isotope. See also *Uranium.*

Thorium is a heavy metal, and in its compounds is tetravalent. Its compounds most closely resemble those of tetravalent cerium, and because of hydrolysis resemble those of tetravalent titanium, zirconium, and hafnium. In many compounds, thorium resembles the rare earths, for example, in the insolubility of the fluorides, carbonates, hydroxides, oxalates, and phosphates. In aqueous solutions, thorium exists in complex ions, often of indeterminate composition. Thorium is basic, resembling ceric cerium in basicity.

Thorium is always associated in nature with the rare earth elements, and their presence complicates the commercial extraction of thorium from the ores.

ANALYSIS

Thorium is generally determined by weighing the oxide obtained by the ignition of the hydroxide or oxalate. Small amounts of thorium may be determined colorimetrically in some applications with 1-(*o*-arsonophenylazo)-2-naphthol-3,6-disulfonic acid (17). In minerals in which thorium is in equilibrium with its radioactive daughter products, it may be determined radiometrically if allowance is made for radioactivity due to any uranium present.

Rocks and minerals are usually brought into solution by fusion with sodium peroxide, ammonium hydrogen fluoride, or potassium bisulfate, followed by the usual analytical techniques to obtain a solution of the thorium. A preliminary isolation of thorium and rare earths is made by oxalate or fluoride precipitation. Thorium is then separated from the thorium – rare earth mixture by precipitation of thorium iodate, thorium pyrophosphate, thorium peroxide, or organic thorium salts such as thorium *m*-nitrobenzoate, thorium benzenearsonate, or thorium sebacate, or by fractional basicity precipitation of thorium hydroxide with hexamine (hexamethylenetetramine) (5). Thorium may also be conveniently separated from rare earths by extraction with mesityl oxide(8). A general method of wide versatility is to isolate the rare earths and thorium as oxalates by precipitation from slightly acid solution. After reprecipita-

tion of the oxalates to remove traces of heavy metals and phosphate which may be present, thorium is precipitated with hexamine from a neutral chloride solution of the oxides obtained by igniting the oxalate precipitate (12).

Monazite is analyzed for thorium by opening with sulfuric acid digestion or sodium peroxide fusion, followed by isolation of thorium by precipitation as iodate, or by isolation of thorium hydroxide from a solution of mixed thorium – rare earth oxalates by precipitation with hexamine. The final determination is made by precipitating thorium oxalate and igniting this to thorium oxide.

Thorium analyses are among the most difficult to make, since many of the thorium salts that can be used to isolate thorium by precipitation are either appreciably soluble, or do not completely separate thorium from accompanying materials. For example, thorium oxalate precipitation neatly separates thorium from many common elements, but it does not separate it from rare earths, and the precipitate is appreciably soluble.

OCCURRENCE

The earth's crust is estimated to contain 10–15 p.p.m. thorium. Found in many minerals, thorium is always associated with varying amounts of rare earths and often with titanium, niobium, tantalum, and uranium. The only mineral of economic importance is monazite, a rare earth – thorium orthophosphate; it is also the principal ore of cerium and the rare earths (see *Cerium*; *Rare earth metals*).

Monazite occurs as monazite sand in stream and beach placers, rarely in vein and pegmatite deposits. Commercial monazite sand deposits are found in Travancore, India, and Espirito Santo, Brazil, and in Idaho, North and South Carolina, and Florida. Massive monazite is mined from deposits in the Van Rhynsdorp district in the Union of South Africa. Monazite varies considerably in thorium content. Although monazites contain from 1 to over 20% ThO_2, commercial monazites contain from 3 to 9% ThO_2: Idaho monazite, 3% ThO_2; Florida monazite, 4% ThO_2; Brazil, Carolina, and South African monazites, 6% ThO_2; and India monazite, 9% ThO_2. Commercial monazites contain 45–65% rare earth oxides in addition to thorium.

Until about 1920, monazite was of value solely for its thorium content, which was used largely to make incandescent gas mantles. Since about 1920, the rare earth content of monazite has been of more importance and the unit price of monazite is based on its content of rare earth oxide or the total of the thorium and rare earth oxides. Before World War II, monazite sold for about $50 per long ton, but since the war this price has risen to $300–450 per long ton, the values depending on the quality of the ore in terms of its content of rare earth oxides.

Other thorium minerals are: thorite, $ThSiO_4$; thorianite, $(Th,U)O_2$; euxenite and samarskite, complex niobate-tantalates of the rare earths, uranium, thorium, zirconium, calcium, and magnesium; and gadolinite, a beryllium–iron–thorium–rare earth–silicate.

EXTRACTION

The methods of extracting thorium from monazite ores are concerned mainly with the separation of thorium from rare earths and from phosphate.

The treatment of monazite ores to isolate crude thorium intermediates is the same as that required to extract rare earths from the ores (see Vol. **3**, pp. 638–39; Vol. **11**, p. 506). The processes used commercially are varied and are carefully guarded arts. However, most processes start with the isolation of a crude thorium residue which is either processed further to make purified thorium materials, or is stockpiled if rare earth production overbalances thorium production. Usually the crude thorium residue is a phosphate (11), pyrophosphate, oxalate, or basic thorium salt precipitate.

Starting with monazite ores containing from 45 to 65% rare earth oxide and 3 to 8% ThO_2, the initial thorium residue obtained from the first bulk separation of rare earths from thorium contains about equal parts of thorium and rare earths. The subsequent commercial purification steps finally produce thorium compounds, such as thorium nitrate, or thorium oxide, which contain 20–200 p.p.m. rare earths.

The purification steps used depend on the nature of the thorium residue. Some of the more important processes are as follows (1):

The addition of sodium carbonate to impure thorium solutions precipitates a basic thorium carbonate mixed with rare earth carbonates. With an excess of sodium carbonate, the thorium carbonate dissolves, forming a soluble complex carbonate. Since the solubility of rare earth carbonates in excess alkali carbonate is small, a separation from rare earths is accomplished. In addition to thorium carbonate, several other water-insoluble thorium salts are soluble in excess alkali carbonate, notably thorium fluoride (20,21).

Similarly, the addition of alkali oxalates to crude thorium solutions first precipitates a mixture of thorium and rare earth oxalates. If excess alkali oxalate is added, the rare earth oxalates remain largely insoluble, while thorium oxalate forms soluble complex oxalates.

Although both thorium fluoride and rare earth fluorides are quite insoluble in acid solutions, thorium fluoride has a lower solubility. This difference in solubility is sufficient to allow thorium fluoride to be fractionally precipitated from thorium–rare earth solutions with hydrofluoric acid (22).

Both thorium- and rare earth–hydrated sulfates are sparingly soluble in water, but the difference in solubility is relatively great, thorium sulfate being the least soluble below 45°C. Fractional crystallization of thorium sulfate at low temperatures effects a separation from rare earths (1).

In practice, a combination of purification methods is used, and the process is complicated because of the many chemical conversions required to change from one thorium salt to another.

After purification, the thorium is finally obtained as a basic carbonate or hydroxide. This is dissolved in nitric acid and crystallized to obtain thorium nitrate approximating the composition $Th(NO_3)_4.4H_2O$, the principal commercial thorium salt.

More recently, solvent extraction procedures have received attention for the recovery and purification of thorium from aqueous solutions. Higher alcohols and ketones preferentially extract thorium from rare earth nitrates (35). Extraction of thorium with 1-butanol from thiocyanate solution also appears to be an effective procedure for separating thorium from rare earths (32). The general behavior of thorium in organic solvents has been discussed by Yaffe (36), Templeton and Hall (34), and by Bock and Bock (33).

Thorium Metal and Thorium Alloys

PROPERTIES

Fresh surfaces of thorium metal are white, but these oxidize in air to dark gray or black coatings. The hardness of the metal is comparable to that of annealed copper. Thorium is malleable and can be machine-rolled, cold-worked, and drawn into wire (10). The metal hardens on working, and its tensile strength is low.

The structure of the metal is face-centered cubic. Densities are 11.6 g./cu.cm.

for massive metal, 11.3 g./cu.cm. for sintered metal, and the x-ray density is 11.7 g./cu.cm. (10,16). The melting point of thorium is 1840 ± 20°C., and the boiling point is about 4500°C.

Water and alkali solutions do not appreciably attack thorium metal. It slowly reacts with sulfuric, nitric, and hydrochloric acids to form soluble salts. The rate of reaction of thorium metal (and some of its refractory compounds such as the oxide) with nitric acid is materially increased if traces of fluorides are added (29). The powdered metal ignites easily in air. Chlorine, bromine, and iodine react with the metal above 450°C., giving the corresponding halide ThX_4. Hydrogen and nitrogen form, respectively, hydrides and nitrides, Th_3N_4 and ThN, above 600–650°C. Sulfur and hydrogen sulfide react at elevated temperatures giving the sulfides ThS and Th_2S_3. Thorium metal is an active reducing agent, comparable to aluminum and magnesium in activity.

PREPARATION OF THORIUM METAL

Starting materials for thorium metal preparation are anhydrous thorium halides, potassium fluorothorate, and thorium oxide.

From thorium chloride, the metal can be prepared by reduction with sodium (6), and by reduction with alkaline earth metals (4), or the double potassium thorium chloride $2KCl.ThCl_4$ (see p. 120) may be treated with sodium. With thorium chloride, the preferable method is to electrolyze the anhydrous salt in a fused mixture of sodium and potassium chlorides; the metal is obtained as a powder which is washed free of salts with water, dried, and sintered to form the massive metal. Anhydrous potassium fluorothorate, $KThF_5$, (see p. 121) can also be similarly electrolyzed in a melt of sodium and potassium chlorides at 750–800°C., in a graphite crucible with a molybdenum cathode, to obtain powdered thorium metal (2,15).

Thorium oxide can be reduced in a bomb at about 1400°C. with sodium or calcium, or by mixtures of calcium or magnesium with calcium chloride or magnesium salts (9,13,23,28). Calcium reduction gives a good grade of metal, but magnesium reduction gives a low-grade powder. Reduction of the dioxide with carbon results in a metal with a high carbon content, and reduction with aluminum gives aluminum-thorium alloys. Thorium can be prepared from thorium oxide using calcium hydride, CaH_2, with hydrogen in retorts at atmospheric pressure. Subsequent cooling in vacuum gives a 99% pure thorium powder after leaching with water to remove calcium hydroxide (30).

By the Arkel-deBoer process, massive thorium can be made by the thermal decomposition of thorium iodide (19).

Powdered thorium metal is made directly by electrolysis of anhydrous thorium chloride or double potassium fluorothorate. From the massive state, it can be made by converting the metal to the powdery thorium hydride ThH_{3-4}, and then removing hydrogen by heating in a vacuum at 700°C. (31). Thorium metal powder can be sintered in a vacuum, and the sintered metal can be forged into massive forms.

Commercial thorium metal is available in powder or massive forms in purities over 99%; the impurities are largely traces of silicon, iron, and thorium oxide.

Thorium metal is used with tungsten or nickel electrodes in gaseous discharge lamps such as high-intensity mercury lamps and cold-cathode germicidal lamps. Thorium is useful in such applications because of its low work function and high electron emission properties.

THORIUM ALLOYS

Although thorium alloys with many metals, the only commercially significant alloys are those with tungsten and magnesium. Tungsten-thorium alloys have been used as filaments in incandescent lights and in photoelectric cells.

Magnesium-thorium alloys containing 3% thorium and 1% zirconium have outstanding high-temperature strength. They have the highest creep resistance at 500–600°F. of any magnesium alloy (9).

Thorium Compounds

Thorium is tetravalent in all its important compounds; other valences are rare or nonexistent. The thorium ion is colorless. Hydrolysis is common, but hydroxides or basic salts are usually not precipitated unless the solutions are very dilute. In concentrated solutions of low acidity, thorium exists as ThO^{2+} or $Th(OH)^{3+}$ ions and possibly as polynuclear thorium complex ions. The constitution of the complex salts of thorium is uncertain; the complex fluorides may contain anions such as pentafluorothorate, ThF_5^-, but the other complex compounds may well be double salts.

Thorium Carbonates.

The addition of alkali or ammonium carbonate to thorium solutions precipitates a basic carbonate, approximately $ThO(CO_3).8H_2O$. The normal anhydrous carbonate cannot be made from aqueous solution. Excess alkali carbonate dissolves thorium carbonate, forming complexes such as $Na_6[Th(CO_3)_5].12H_2O$ and $(NH_4)_2[Th(CO_3)_3].6H_2O$. Thorium carbonate is a useful intermediate in the preparation of other thorium compounds.

Thorium Halides.

Thorium chloride, $ThCl_4$, formula weight 373.95, is made in hydrated form by crystallizing a solution of thorium hydroxide or carbonate in concentrated hydrochloric acid. Sufficient acid must be present during crystallization to prevent hydrolysis and the precipitation of basic thorium chloride. Thorium chloride is extremely soluble in water, and is hygroscopic. The solution of thorium hydroxide in insufficient hydrochloric acid to form the normal salt forms soluble hydrated hydroxychlorides such as $Th(OH)_2Cl_2.5H_2O$. Double alkali metal and ammonium chlorides of the type $KCl.ThCl_4$ and $2KCl.ThCl_4$ exist but are not important.

Anhydrous thorium chloride is prepared by the action of phosgene or carbon tetrachloride on heated thorium oxide, or by the dehydration of the hydrated chloride with ammonium chloride at 650–700°C. Anhydrous thorium chloride sublimes at about 750°C., melts at 770°C., and boils at 921°C. It is important in the production of thorium metal.

Thorium bromide, $ThBr_4$, and **iodide,** ThI_4, exist but are not important. They are made by the action of bromine or iodine on thorium metal. Anhydrous thorium bromide is also made by heating thorium oxide with carbon in a stream of bromine.

Thorium iodate, $Th(IO_3)_4$, formula weight 931.80, is precipitated when solutions of thorium salts are treated with aqueous potassium iodate. The precipitate is insoluble in 4 *N* nitric acid, whereas the rare earth iodates are soluble, and for this reason it is important in thorium analysis. Thorium iodate is similar to ceric iodate.

Thorium fluoride, $ThF_4.8H_2O$, formula weight 452.24, precipitates when hydrofluoric acid or a soluble fluoride is added to thorium solutions. Most of the water of hydration is lost on drying, and on ignition, thorium oxyfluoride, $ThOF_2$, and finally thorium oxide, ThO_2, are formed. Thorium fluoride is insoluble in mineral acids and excess hydrofluoric acid. Anhydrous thorium fluoride is made by heating thorium oxide, or anhydrous thorium halides, in a stream of anhydrous hydrogen fluoride. With sodium and potassium fluorides, thorium fluoride forms fluothorates such as $KThF_5$ and K_2ThF_6. These are prepared by fusing thorium fluoride with the alkali metal fluoride, or by adding hydrofluoric acid to thorium solutions containing the alkali metal fluoride.

Thorium Hydrides.

Heating thorium metal in hydrogen at 400–600°C. forms the dihydride, ThH_2. At 100°C., the dihydride absorbs hydrogen, forming ThH_{3-4}. At temperatures above 700°C., the hydrides dissociate to thorium metal. Thorium hydrides when pure react slowly with water and ignite spontaneously in air.

Thorium Nitrate.

Thorium nitrate approximating the composition $Th(NO_3)_4.4H_2O$ is crystallized from slightly acid solutions made by treating thorium carbonate or thorium hydroxide with nitric acid. It is very soluble in water, and is the chief commercial thorium compound. Hydrates with 2, 4, 5, 7, and 12 molecules of water are known. Double nitrates with alkali and alkaline earth metals are known but are not important.

Thorium Oxalate.

Like the rare earth oxalates, thorium oxalate is insoluble in water and dilute acids. It is obtained by the addition of oxalic acid or alkali oxalates to thorium solutions, from which it precipitates as a finely crystalline hydrate, $Th(C_2O_4)_2.6H_2O$. With excess alkali and ammonium oxalate, thorium oxalate is dissolved, forming soluble complex salts such as $(NH_4)_4[Th(C_2O_4)_4].4H_2O$.

Thorium Oxides and Hydroxide.

Thorium hydroxide, $Th(OH)_4$, formula weight 300.15, is extremely insoluble in water (solubility product 10^{-39}) and is precipitated by the addition of alkali and ammonium hydroxides to aqueous thorium solutions. It can also be prepared by the action of alkali hydroxides on insoluble and sparingly soluble salts such as thorium sulfate and thorium oxalate. Freshly prepared, undried thorium hydroxide readily reacts with acids to form soluble thorium salts. On drying, thorium hydroxide gives hydrated thorium oxides of variable composition which are less reactive.

Thorium oxide (thoria), ThO_2, formula weight 264.12, is made by roasting thorium hydroxide or thorium salts of volatile acids, such as thorium oxalate or thorium nitrate. The oxide is a white powder, and its bulk depends on its method of preparation. Ignition of the oxalate gives a relatively bulky powder, but thorium nitrate and sulfate give dense powders. Thorium oxide has the highest melting point of any oxide (about 3220°C.), and its boiling point is about 4400°C. Fused thorium oxide is made from the powder by fusion in an induction or carbon arc furnace.

Thorium peroxide, $Th_2O_7.4H_2O$, formula weight 648.30, is precipitated when hydrogen peroxide is added to slightly acid, neutral, or slightly basic solutions. The composition of the precipitate is variable, and it contains anions from the solution. The compound $ThOOSO_4.3H_2O$ is precipitated from hot dilute sulfuric acid solution. Thorium peroxide precipitation is sometimes used analytically to separate thorium from rare earths.

Thorium Phosphates.

Thorium orthophosphate, $Th_3(PO_4)_4.4H_2O$, formula weight 1148.34, is precipitated from acid thorium solutions by soluble orthophosphates or orthophosphoric acid. It is a gelatinous precipitate, soluble in concentrated acids and large excesses of phosphoric acid.

Thorium pyrophosphate, $ThP_2O_7.2H_2O$, formula weight 442.11, is precipitated from acid thorium solutions by alkali pyrophosphates. It is a useful salt for separating thorium from the rare earths, since rare earth pyrophosphates are soluble in acid solutions. Excess alkali pyrophosphates dissolve thorium pyrophosphate, forming complexes such as $Na_4[Th(P_2O_7)_2]$.

Thorium Sulfate.

Thorium sulfate, $Th(SO_4)_2$, formula weight 424.25, is precipitated in hydrated form as fine crystals when sulfuric acid is added to thorium nitrate or thorium chloride solutions. At temperatures below 43°C., the enneahydrate, $Th(SO_4)_2.9H_2O$ forms, and above 43°C. the tetrahydrate is obtained. The hexa- and octahydrates are also known. All form the dihydrate on drying at 100°C. Anhydrous thorium sulfate is made by drying the hydrated salts at 400°C., or by heating thorium oxide, hydroxide, or carbonate with concentrated sulfuric acid. Thorium sulfate is moderately soluble in water. The solubility of the enneahydrate increases with temperature, but that of the tetrahydrate decreases with increasing temperature.

Double sulfates of the alkali and alkaline earth sulfates with thorium sulfate are known. These salts are more soluble than thorium sulfate.

Thorium Sulfides.

Thorium forms several sulfides which are interesting because of their refractory nature. Heating thoria in hydrogen sulfide at 1200–1300°C. gives **thorium oxysulfide,** ThOS, which is converted to **thorium disulfide,** ThS_2, on continued heating in hydrogen sulfide. When heated to 1950°C., ThS_2 is converted to the lower sulfides Th_4S_7 and Th_7S_{12}. Sulfides lower than ThS_2 can be made by heating ThS_2 with the proper amount of thorium hydride, first at 400–600°C. to decompose the hydride, and then at 2000–2200°C. to form the sulfide. All of these sulfides can be made by heating thorium hydride with hydrogen sulfide, first at 400–500°C., and finally at 1800–1900°C. after grinding the intermediate product (3).

All of the thorium sulfides may be used for high-temperature refractory containers in a vacuum or in inert atmosphere at temperatures up to 1500–2200°C. They are slowly attacked by dilute acids, but in the sintered form they are stable in air and in boiling water.

GRADES AND SPECIFICATIONS

The several grades of thorium nitrate available commercially are all highly purified materials. Variations in grades are largely a matter of differences in the content of impurities. The usual thorium nitrate of commerce approximates the composition $Th(NO_3)_4.4H_2O$, and analyzes 46–47% ThO_2. Impurities are present in the following approximate amounts: rare earths, 0.002–0.01%; P_2O_5, 0.001–0.05%; Fe_2O_3, 0.0001–0.020%; CaO and MgO, 0.2–0.1% each; SiO_2, 0.004%; Cl, 0.001%; and alkali metal salts, 0.05–0.2%. "Mantle-grade" thorium nitrate contains sulfate (0.5–1% SO_3), which is intentionally added (see Vol. 8, p. 195).

Thorium oxide is next to thorium nitrate in importance. It is made commercially in grades approximating those of thorium nitrate, and in varying degrees of apparent density. Thorium fluoride, thorium chloride, thorium carbonate, and thorium sulfate are of lesser importance.

ECONOMIC ASPECTS

From 1900 to about 1920 when the gas-mantle industry was in its prime, thorium nitrate was the only important product obtained from monazite ore. Relatively small amounts of rare earth materials were obtained as by-products from the refining of thorium nitrate. As use of the gas mantle declined after about 1920, thorium became a by-product of rare earth refining.

Thorium nitrate prices for large lots in 1954 were about \$3 to \$4 per pound depending on the purity of the preparation. Considering the cost of monazite ore, it is apparent that this price structure is based on at least a partial balance between the production of rare earth and thorium compounds, since both are obtained primarily from monazite. Thorium oxide prices range from \$7 to \$8 per pound, the cost varying with the purity.

The mining, possession, sale, and purchase of thorium materials are controlled by the Atomic Energy Commission.

USES

In spite of widespread use of electricity for illumination, the largest single commercial use for thorium is its utilization as thorium nitrate in the manufacture of gas mantles (see Vol. 8, pp. 192–97).

The atomic energy use of thorium materials is based on its conversion by an (n,γ) reaction to fissionable $_{92}U^{233}$:

$$_{90}Th^{232}(n,\gamma)_{90}Th^{233} \xrightarrow[23\ min.]{\beta^-} {}_{91}Pa^{233} \xrightarrow[27\ days]{\beta^-} {}_{92}U^{233}$$

Thorium oxide is used in silica-free rare element optical glass (24,25,26), and thorium fluoride has been suggested for the same application (27). The high melting point of thorium oxide makes it valuable for crucibles and refractories for high temperature service (14).

Thoriated tungsten consists of 1–2% ThO_2 dispersed in a tungsten matrix, and is made by adding thorium nitrate to tungstic acid before reduction to the metal. It has a low work function and high electron emission, and therefore is important as a filament in electron vacuum tubes. The presence of thoria also stabilizes the crystal growth of tungsten in the filament, and such filaments are used in lamps which are subject to vibration. Thoriated tungsten is also used for nonconsumable electrodes in inert-gas-shielded arc welding.

Although colloidal thorium oxide sols have been used as shadowing agents for human radiography, this use has dwindled because the natural radioactivity of thorium may have contributed to the formation of cancers. Thorium oxide makes a good optical glass polish, and in a crude form was used for this purpose during World War II by the Germans, but it cannot compete with conventional optical polishes such as ceric oxide, rare earth oxide, and rouge. Thorium oxide can be used as a dehydrogenation catalyst for the preparation of ketones from monocarboxylic acids, and for the conversion of alcohols to ethers or olefins. In the laboratory, thorium nitrate is used as a reagent for the volumetric determination of fluoride.

Bibliography

(1) Caven, R. M., "Thorium and Its Compounds," in Friend, *A Textbook of Inorganic Chemistry*, Griffin, London, 1921, Vol. V, ch. 6.
(2) Driggs, F. H., and Lilliendahl, W. C., *Ind. Eng. Chem.*, **22**, 1302 (1930).
(3) Eastman, E. D., *et al.*, *J. Am. Chem. Soc.*, **72**, 4019 (1950).
(4) Groggin, J. F., Cronin, J. J., Fogg, H. C., and James, C., *Ind. Eng. Chem.*, **18**, 114 (1926).
(5) Ismail, A. M., and Harwood, H. F., *Analyst*, **62**, 185 (1937).
(6) Lely, D., Jr., and Hamburger, L., *Z. anorg. Chem.*, **87**, 209 (1914).
(7) Leontis, T. E., *J. Metals*, **4**, 287–94 (1952).
(8) Levine, H., and Grimaldi, F. S., *U.S. Geol. Survey, Trace Elements Lab. Invest.*, **7** (1950).
(9) Marden, J. W., and Rentschler, H. C., *Ind. Eng. Chem.*, **19**, 97 (1927).
(10) Meister, G., *U.S. Atomic Energy Comm. Rept.* **MDDC-1673** (1948).
(11) Pilkington, E. S., and Wylie, A. W., *J. Soc. Chem. Ind.*, **66**, 387 (1947).
(12) Rodden, C. J., and Warf, J. C., "Thorium," in Rodden, *Analytical Chemistry of the Manhattan District, National Nuclear Energy Series*, McGraw-Hill, N.Y., 1950, Vol. VIII-1, ch. 2.
(13) Ruff, O., and Brintzinger, H., *Z. anorg. Chem.*, **129**, 272 (1923).
(14) Schwartz, M. A., White, G. D., and Curtis, C. E., *U.S. Atomic Energy Comm. Rept.*, **ORNL-1354** (1953).
(15) Sibert, M. E., and Steinberg, M. A., *U.S. Atomic Energy Comm. Rept.*, **NYO-3725** (1952).
(16) Sidles, P. H., and Danielson, G. C., *J. Applied Phys.*, **25**, 66 (1954).
(17) Thomason, P. F., Perry, M. A., and Byerly, W. M., *Anal. Chem.*, **21**, 1239–41 (1949).
(18) Urie, R. W., *J. Soc. Chem. Ind.*, **66**, 437 (1947).
(19) Veigel, N. D., Sherwood, E. M., and Campbell, I. E., *U.S. Atomic Energy Comm. Rept.*, **AECD-3586, BMI-777** (1953).
(20) Brit. Pat. 129,624 (April 4, 1919), Lindsay Light Co.
(21) U.S. Pat. 1,307,153 (June 17, 1919), L. W. Ryan (to Lindsay Light Co.).
(22) U.S. Pat. 1,335,157 (March 30, 1920), O. Dietsche (to the Chemical Foundation).
(23) U.S. Pat. 1,738,669 (Dec. 10, 1929), M. N. Rich (to Westinghouse Lamp Co.).
(24) U. S. Pat. 2,150,694 (May 14, 1939), G. W. Morey (to Eastman Kodak Co.).
(25) U.S. Pat. 2,241,249 (May 6, 1941), L. W. Eberlin and P. F. De Paolis (to Eastman Kodak Co.).
(26) U.S. Pat. 2,466,392 (April 5, 1949), P. F. De Paolis (to Eastman Kodak Co.).
(27) U.S. Pat. 2,466,505–9 (April 5, 1949), K-H Sun (to Eastman Kodak Co.).
(28) U.S. Pat. 2,446,662 (July 27, 1948), H. C. Rentschler, W. C. Lilliendahl, and J. E. Gray (to Westinghouse Electric Co.).
(29) U.S. Pat. 2,546,933 (March 27, 1951), F. L. Steahly, R. W. Stoughton, and F. W. Schuler (to U.S. Atomic Energy Commission).
(30) U.S. Pat. 2,584,411 (Feb. 5, 1952), P. P. Alexander (to Metal Hydrides, Inc.).
(31) U.S. Pat. 2,635,956 (April 21, 1953), H. A. Wilhelm and P. Chiotte (to U.S. Atomic Energy Commission).
(32) Asselin, G. F., Audrieth, L. F., and Comings, E. W., *J. Phys. & Colloid Chem.*, **54**, 640–48 (1950).
(33) Bock, R., and Bock, E., *Z. anorg. u. allgem. Chem.*, **263**, 146–168 (1950).
(34) Templeton, C. C., and Hall, N. F., *Can. J. Research*, **28**, 156–60 (1950).
(35) Templeton, C. C., and Hall, N. F., *J. Phys. & Colloid Chem.*, **54**, 954–57, 958–65 (1950).
(36) Yaffe, L., *Can. J. Research*, **28**, 171 (1950).

H. E. KREMERS

THORTVEITITE, $ScSi_2O_7$. See *Silica and silicates (mineral)*, Vol. **12,** p. 279.

THREITOL, $CH_2OH(CHOH)_2CH_2OH$. See *Alcohols, polyhydric*, Vol. **1,** p. 322.

THREONINE, $CH_3CH(OH)CH(NH_2)COOH$. See *Amino acids*, Vol. **1,** pp. 719, 720.

THREOSE, $C_4H_8O_4$. See *Sugars (survey)*, Vol. **13,** p. 232.

THROMBIN. See *Hemostatics*, Vol. **7,** p. 420.

THUCHOLITE. See *Uranium.*

THUJANE, $C_{10}H_{18}$; α(and β)-**THUJENE,** $C_{10}H_{16}$. See *Hydrocarbons*, Vol. **7,** pp. 609, 610; *Terpenes (mono-, cyclic)*, Vol. **13,** p. 727.

THUJA OIL. See *Oils, essential*, Vol. **9,** p. 590.

THUJONE, $C_{10}H_{16}O$. See *Terpenes (mono-, cyclic)*, Vol. **13,** p. 737.

THULIUM. See *Rare earth metals.*

THYME. See *Emetics and expectorants*, Vol. **5,** p. 684.

THYME OIL. See *Oils, essential*, Vol. **9,** p. 590.

THYMIDYLIC ACID, $C_{10}H_{15}N_2O_8P$. See *Nucleic acids*, Vol. **9,** pp. 508, 509.

THYMINE, $\underline{NH.CO.NH.CO.C(CH_3):CH}$; **THYMIDINE,** $C_{10}H_{14}N_2O_5$. See *Nucleic acids*, Vol. **9,** pp. 509, 510.

THYMOL, $CH_3(C_3H_7)C_6H_3OH$. See *Antiseptics*, Vol. **2,** p. 85; *Cresols*, Vol. **4,** p. 606; *Perfumes (synthetics and isolates)*, Vol. **10,** pp. 25, 31.

THYMOL BLUE; THYMOLPHTHALEIN. See *Indicators*, Vol. **7,** p. 805.

THYMUS HORMONES. See *Hormones (miscellaneous)*, Vol. **7,** p. 548.

THYNNIC ACID, $C_{25}H_{39}COOH$. See *Fatty acids (marine-oil)*, Vol. **6,** p. 286.

THYRATRONS. See *Electronics*, Vol. **5,** p. 560.

THYROID AND ANTITHYROID PREPARATIONS

The thyroid gland plays an extremely important role in the animal body by means of its effect on the basal metabolic rate (B.M.R.), which is a measure of the energy expended by the body at rest. This control of metabolism is mediated through an endocrine substance, the thyroid hormone, produced by the gland in response to nervous or hormonal stimuli (see also *Hormones (survey)*). The hormone thus released into the circulation appears to affect cellular metabolism directly. Abnormal activity of the thyroid gland occurs fairly frequently in man, and often requires medical treatment to adjust the situation to within normal limits. Shortage of thyroid secretion (hypothyroidism, cretinism, myxedema) can be alleviated by careful administration of desiccated thyroid tissue or purified preparations therefrom. Dosages are generally worked out on an individual basis to bring the metabolic rate to normal and to maintain it. The overproduction of thyroid hormone in man leads to hyperthyroidism (exophthalmic goiter, Graves' disease, toxic goiter), characterized by nervousness, protruding eyeballs, and reduction in weight. Hyperthyroidism may be treated with antithyroid substances (see p. 132), although surgical removal of most of the overactive thyroid gland (subtotal thyroidectomy) is often necessary as well. The operation is usually followed by the administration of thyroid preparations for fine adjustment to normal levels of metabolism. Thyroid preparations may be used also in a

third type of thyroid disorder, simple goiter, which occurs especially in inland and mountainous areas where water and foods are low in iodine. However, this difficulty can generally be controlled by incorporation of adequate amounts of iodine in the diet as in iodized salt or drinking water, which has been practiced extensively since about 1910. Similar abnormalities occur in animals or may be brought about experimentally, and these serve in certain instances as bases for assay of thyroid activity.

THYROID PREPARATIONS

Natural thyroid preparations showing biological activity include (*1*) dried, defatted whole thyroid tissue (thyroid, U.S.P. XIV); (*2*) iodine-containing protein fractions therefrom; (*3*) thyroglobulin, the purified thyroid protein; and (*4*) thyroxine, the iodinated amino acid found in hydrolyzates of thyroid tissue and thought to be the circulating hormone. In addition, there are artificially iodinated proteins for which biological activity has also been shown. Each of these has specific applications for which it is best suited. For oral administration and maintenance therapy the whole tissue preparations, standardized as to potency, are generally used. The purified fraction (thyroglobulin) and thyroxine are more suitable for parenteral administration. Thyroglobulin has had little commercial use because of its cost, but has provided considerable information regarding the role of the thyroid hormone in metabolism. Synthetic iodoproteins have been used primarily in animals to increase metabolic and growth rates, rather than for control of human thyroid abnormalities. (See also *Iodine preparations*, Vol. **7**, pp. 979–80.) Some question as to the economics of such growth stimulation has resulted from measurement of the increased food intake of treated animals over that of controls.

The oral administration of thyroid substances was begun about 1895, but extensive use of such materials did not take place until about 1910. While earlier attempts were made to show a relationship between iodine and the thyroid gland, Baumann in 1895 showed that iodine in organic combination was a constituent of thyroid tissue. Oswald in 1899 gave the name "thyroglobulin" to the iodine-containing globulin in thyroid. Later it was demonstrated that the physiological action of whole thyroid tissue was directly proportional to its protein-bound iodine content.

Study of thyroid glands of domestic animals showed seasonal variation of the iodine content (3) amounting to a twentyfold difference in beef glands, with a similar range in hog glands. This emphasized the necessity of standardizing thyroid preparations. These findings led to the establishment by the U.S.P. in 1917 of a standard thyroid preparation with 0.20 ± 0.03% iodine.

Attempts to isolate a specific iodine compound were unsuccessful until Kendall (9), in 1914, obtained thyroxine from a hydrolyzate of thyroid glands. The chemical structure of thyroxine was established in 1926 and the compound was synthesized in 1927 (7) (see p. 129). Kendall's other iodine fraction was identified in 1929 as diiodotyrosine. While both iodine compounds are cleavage products of thyroglobulin in which they are in combined forms for purposes of storage, diiodotyrosine is inactive in practical amounts, while thyroxine shows thyroid activity upon parenteral injection. Approximately forty per cent of thyroid iodine is estimated to be in the form of thyroxine and 60% as diiodotyrosine.

Physical and Chemical Properties

Thyroid substance (thyroid, U.S.P. XIV) is the cleaned, dried, powdered thyroid gland previously deprived of connective tissue and fat, which contains not

less than 0.17% and not more than 0.23% of iodine. It must be free from iodine in inorganic or any form of combination other than that peculiar to the thyroid gland (17). If properly prepared, it will contain less than 1% fat and 1% moisture. It retains its biological activity under ordinary conditions of storage for a number of years without appreciable change.

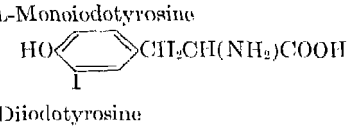
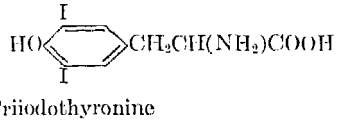
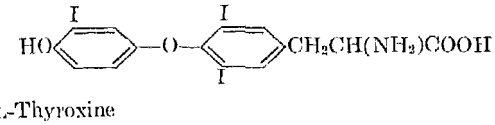
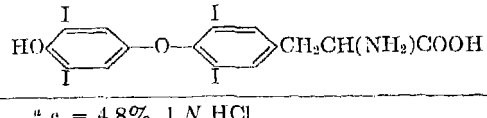
Thyroglobulin seems to exist in three forms differing in solubility but with the same iodine–nitrogen ratio. The three forms are thought to be the same protein. Physical measurements indicate a molecular weight for thyroglobulin of 650,000–700,000. Its amino acid composition shows differences from that of other tissue globulins, but the most important difference is its iodine content. The amino acid composition (15) of hog thyroglobulin is given in Table I.

TABLE I. Composition of Hog Thyroglobulin.

Amino acid	% of total protein	Amino acid	% of total protein
Arginine	12.72	Cystine	3.60
Histidine	2.23	Methionine	1.30
Lysine	3.42	Alanine	7.40
Phenylalanine	6.68	Glycine	3.70
Tryptophan	2.08	Leucine	12.80
Tyrosine	3.12	Valine	1.45
Diiodotyrosine	0.54	Serine	10.80
Thyroxine	0.21		
	Total iodine	0.48%	
	Isoelectric point	4.8	

There appear to be only small variations in amino acid composition among thyroglobulin preparations from several species of domestic animals. The total iodine content, however, may vary within species depending upon season, geographical location, and state of nutrition.

TABLE II. Iodinated Amino Acids.

Name and formula	Formula wt.	M.p., °C.	Iodine, %	$[\alpha]_D^{20}$
L-Monoiodotyrosine 	307.1	204–06 (decompn.)	41.3	−4.4[a]
Diiodotyrosine 	433.0	204 (decompn.)	58.6	+2.75[a]
Triiodothyronine 	650.9	233–34 (decompn.)	58.5	+21.5[a]
L-Thyroxine 	776.9	235–36 (decompn.)	65.3	−4.4[b]

[a] c = 4.8%, 1 *N* HCl.
[b] c = 3%, 0.13 *N* NaOH and 70% ethyl alcohol.

Iodinated amino acids first isolated from thyroid tissue and later synthesized are thyroxine (tetraiodothyronine) and diiodotyrosine. More recent investigations, employing tracer and chromatographic methods of analysis, have demonstrated the presence of 3,3′,5-triiodothyronine (5) and monoiodotyrosine (16) as normal components of the thyroid. The iodinated thyronines are biologically active, while the iodinated tyrosines are inactive.

The structural formulas of these amino acids and physical constants are given in Table II. These substances show little or no solubility in water as free acids, but are soluble in dilute solutions of the alkali hydroxides and in hot solutions of the carbonates. See also *Amino acids.*

Iodinated Proteins. Iodinated casein, prepared under optimal conditions, contains 7–8% iodine, representing approximately 3% thyroxine when assayed biologically. Isolation of crystalline thyroxine from iodinated casein has been accomplished by procedures employed in crystallization of thyroxine from thyroid tissue (13). Other proteins, including serum albumin, serum globulins, edestin, egg albumin, and silk fibroin have been iodinated in similar fashion and show similar biological activity.

Methods of Preparation

For the natural products, sheep, pork, and beef thyroid tissue are used and may be interchanged whenever an indication of species sensitivity or resistance is encountered.

Thyroid substance (thyroid, U.S.P. XIV) is generally prepared by collecting selected fresh glands at the slaughterhouse and freezing them as soon as possible. The frozen glands are then transported to the pharmaceutical plant where they are ground and dried under vacuum to low moisture content. The dehydrated tissue is extracted with fat solvents such as toluene, benzene, or petroleum derivatives to reduce its lipide content to less than 1%. The defatted material is milled to a fine powder and blended with other lots or with lactose to adjust the organic iodine content to $0.20 \pm 0.03\%$.

Tableting of the thyroid substance is then carried out in the usual manner (see Vol. **10,** p. 237), using lactose or other carbohydrate as the diluent. The tablets are carefully checked for iodine content and for biological activity before release. To improve the acceptability of the preparations for continued use, formulations of thyroid include such variations as enteric coatings; smaller, more compact tablets; and several combinations with the B vitamins.

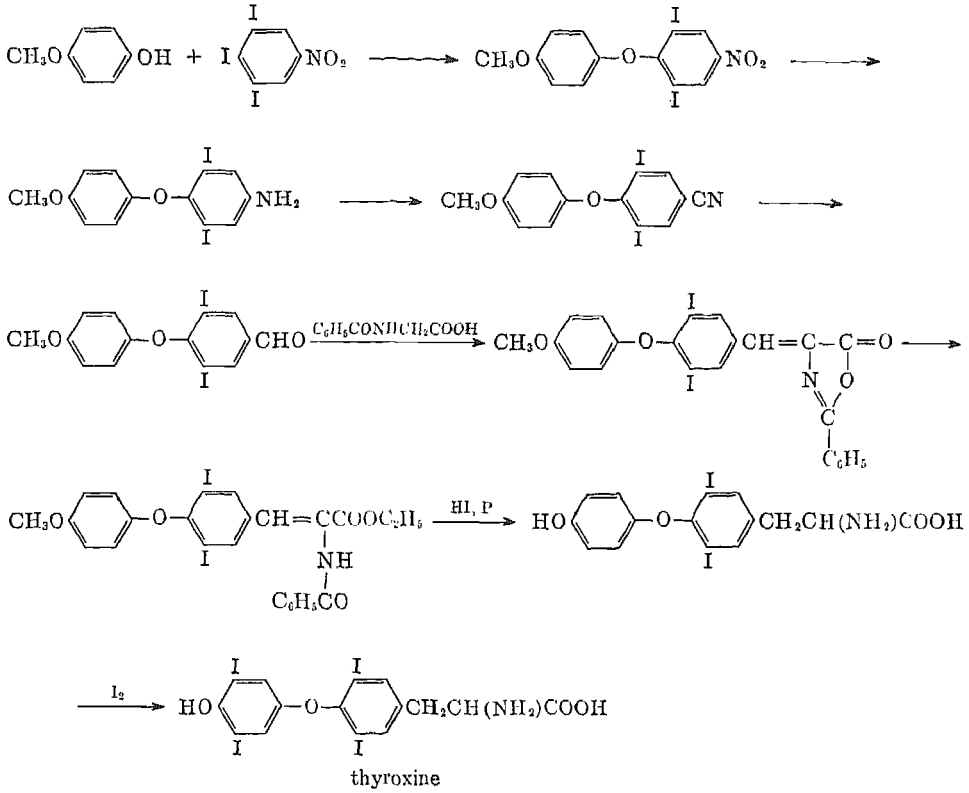
Some of the early steps used in preparation of thyroglobulin are employed in preparation of purified thyroid substance when products higher in iodine content and more soluble than thyroid U.S.P. are desired. It is estimated that domestic production of thyroid products is about 60,000 lb. (U.S.P. equivalent)/year.

Purified thyroglobulin was investigated by early workers who established the globulin nature of the active protein of the thyroid, but their attempts to fractionate it generally led to denaturation of the protein. Methods described by Cavett and Seljeskog (1) avoided contamination with nucleoproteins by extracting thin slices of thyroid gland at 0°C. with isotonic saline at pH 7.4, followed by precipitation of the active material at 35–45% saturation with ammonium sulfate. Similar methods were further used by Derrien, Michel, Pedersen, and Roche (2) to prepare thyroglobulins that satisfy most of the criteria of purity.

Thyroxine. The first synthesis of thyroxine was described by Harington (7) in 1927 (see Scheme 1). The synthetic compound was shown to have biological activity equivalent to that derived from thyroid tissue by early isolation procedures which caused racemization of the more active L-form.

Later reports (14) established optimal conditions for the formation of L-thyroxine from L-tyrosine by way of diiodotyrosine. In a solution of 0.1 *N* sodium hydroxide at pH 9.5, diiodotyrosine was heated with stirring at 60 °C. for 18–20 hours in the presence

SCHEME 1



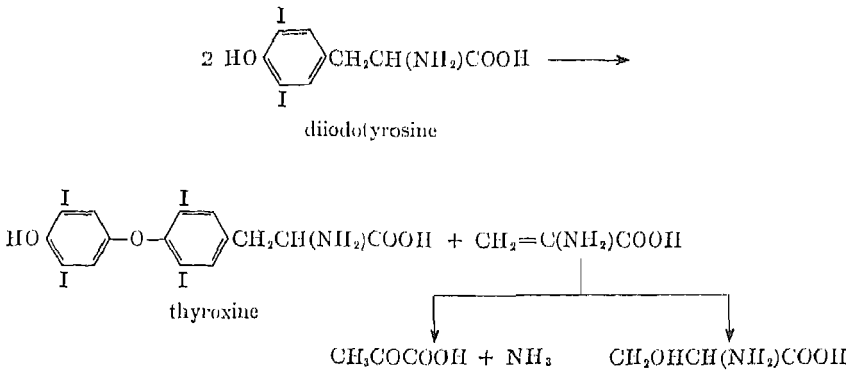
of manganese dioxide catalyst. Under these conditions, a net yield of 2.8% (allowing for recovery of unreacted diiodotyrosine) of crystalline thyroxine was obtained (see Scheme 2). It is assumed that a similar reaction takes place in the thyroid and that thyroxine is probably formed by the oxidative coupling of two molecules of diiodotyrosine and the elimination of one side chain.

Triiodothyronine. No commercial methods for preparation of this compound have been reported. Amounts sufficient for chemical and biological studies have been prepared by careful iodination of diiodothyronine (6).

Iodinated Caseins. Details of the preparation of biologically active iodinated casein have been described by Reineke (13).

Twenty grams of casein is placed in 700 ml. of distilled water containing 5 g. of sodium bicarbonate, and dissolved by stirring. The mixture is then placed in a water bath held at 38–40 °C., and a total of 3.7 g. of finely powdered iodine is added in small

SCHEME 2



portions over a period of 3–4 hours, with vigorous agitation. Following addition of iodine, the solution is vigorously stirred at 70°C. for 18–20 hours. After dialysis, the protein is recovered by isoelectric precipitation and dried. (See also p. 128.)

Assay

Although much study has been given to thyroglobulin as the active protein hormone of the thyroid, present preparations of thyroid in the United States generally adhere to the iodine specifications of 1917 (17). The U.S.P. XIV chemical method for determination of organic iodine involves its conversion to inorganic iodate and measurement by the usual methods of iodometry using standard thiosulfate and starch indicator.

Chemical analysis (13) of the thyroxine content of thyroid substance or of iodinated proteins is accomplished by first hydrolyzing the protein with 40% barium hydroxide at 100°C. for 18–20 hours. The hydrolysis mixture is diluted, the barium salts decomposed, and the aliquots extracted with 1-butanol from acid solution. After extraction of the 1-butanol solution with 4 *N* NaOH containing 5% sodium bicarbonate, the iodine remaining in the organic solvent is then determined and thyroxine content calculated.

Methods designed to measure biological activity of thyroactive materials have also been used.

Stimulation of the metamorphosis of frog tadpoles, a procedure described by Wokes (18), for the assay of thyroid preparations involves measurement of the percentage decrease in body length of tadpoles. Application of this method to iodinated proteins indicates that these materials are active when fed or injected, but not, like thyroid substance, when placed in solution in the water surrounding the tadpoles. The sensitivity of the method varies with the species, stage of development, and temperature of the environment (13).

Change in the metabolic rate of laboratory animals by the measurement of either carbon dioxide production or body weight loss has been placed on a quantitative basis (11).

Reversal of the effect of thiouracil (see p. 134) in chicks, mice (4), and thyroidectomized rats (12) has also been used for assay of thyroid preparations.

Biological Action

The growth and maturation of animals are under the control of the thyroid gland. In fact, all periods of physiological stress require additional thyroid hormone, and it is during such phases of hyperactive metabolism that symptoms of thyroid insufficiency are first observed. Much of present knowledge of thyroid action comes from observation of physiological changes occurring in the absence of the thyroid gland. It appears to act primarily as a catalyst on the metabolism of proteins, carbohydrates, fats, and salt balance. In its absence the basal metabolic rate declines, with noticeable drop in body temperature. Thyroid contributes about 40% of total body metabolism—the balance of 60% being unaffected by the stimulus of thyroid hormone. This is the result if an ordinary diet is given. However, if care is taken to give a diet as free as possible of all traces of iodine, the B.M.R. decreases as much as 60%. The explanation for this is not clear, but it is possible that even without a thyroid gland some tyrosine is converted to thyroxine. The rate of production of thyroxine would be very slow, and this may be why the B.M.R. cannot be held above −60%. Also, at such a low level, secondary changes of appetite, circulation, body temperature, the system of endocrine glands, and many other factors may ultimately influence the B.M.R. (10).

The effect of thyroid on protein, salt, and water metabolism is also readily demonstrated by an accumulation of these substances in the absence of thyroid activity. This accumulation in the tissue spaces is called "proteinous dropsy" and is reversed by administration of thyroid. Thyroid action on carbohydrate metabolism appears to have its effect in the liver, where it tends to mobilize glycogen and to raise the blood sugar level. The relationship between thyroid and diabetes has received considerable attention (8). Subnormal thyroid activity lessens the severity of diabetic symptoms, and administration of thyroid substance with consequent increase in metabolic activity tends to intensify diabetes.

The ability of the thyroid to absorb iodine and, in fact, to pick up most, if not all, of the iodine administered, is postulated as the basis for economy of the body's use of iodine. With the use of radioactive iodine, I^{131}, it has been possible to study the phenomenon in detail. Present evidence is that thyroxine or a small peptide containing it represents the circulating thyroid hormone. There is not yet available sufficient evidence to determine the basic mechanism of action of the circulating thyroid hormone. No *in vitro* systems have been found that will permit study of the peripheral activity of thyroxine. It is generally agreed that dietary iodide is stored in the thyroid gland and converted to iodine, which in turn is incorporated into thyroglobulin. Release of thyroxine or other iodinated small molecules (triiodothyronine) from the thyroid into the circulation may be accomplished by specific proteinases in the gland (5). Ultimate destruction of thyroxine is followed by pickup of the iodine again by the thyroid, and only a small fraction of the iodine is eliminated in the process. Approximately one-seventh of the daily iodine requirement of the thyroid gland is supplied in the normal diet, the balance being supplied by recycling of iodine.

Bibliography for Thyroid Preparations

(1) Cavett, J. W., and Seljeskog, S. R., *J. Biol. Chem.*, **100**, xxvi (1933).
(2) Derrien, Y., Michel, R., Pedersen, K. O., and Roche, J., *Biochim. Biophys. Acta*, **3**, 436 (1949).
(3) Fenger, F., and Seidell, A., *U.S. Pub. Health Serv. Bull.*, **96**, 67 (1914).
(4) Gaddum, J. H., and Hetherington, M., *Quart. J. Pharm. Pharmacol.*, **4**, 183 (1931).
(5) Gross, J., and Pitt-Rivers, R., "Recent Knowledge of the Biochemistry of the Thyroid Gland,"

in Harris, Marrian, and Thimann, *Vitamins and Hormones*, Academic Press, N.Y., 1953, Vol. XI, pp. 159–71.
(6) Gross, J., and Pitt-Rivers, R., *Biochem. J.*, **53**, 645 (1953).
(7) Harington, C. R., and Barger, G., *Biochem. J.*, **21**, 169 (1927).
(8) Houssay, B. A., "The Thyroid and Diabetes," in Harris and Thimann, *Vitamins and Hormones*, Academic Press, N.Y., 1946, Vol. IV, pp. 188–206.
(9) Kendall, E. C., *J. Am. Med. Assoc.*, **64**, 204 (1915).
(10) Kendall, E. C., Personal Communication (1954).
(11) Kreitmair, H., *Z. ges. exptl. Med.*, **61**, 202 (1928).
(12) Meyer, A. E., and Wertz, A., *Endocrinology*, **24**, 683 (1939).
(13) Reineke, E. P., "Thyroactive Iodinated Proteins," in Harris and Thimann (see ref. 8), pp. 207–53.
(14) Reineke, E. P., and Turner, C. W., *J. Biol. Chem.*, **162**, 369 (1946).
(15) Roche, J., and Michel, J., "Natural and Artificial Iodoproteins," in Anson, Edsall, and Bailey, *Advances in Protein Chemistry*, Academic Press, N.Y., 1951, Vol. VI, p. 253.
(16) Taurog, A., Tong, W., and Chaikoff, I. L., *J. Biol. Chem.*, **184**, 83 (1950).
(16a) "The Thyroid," *Brookhaven Symposia in Biology*, No. 7 (1955).
(17) U.S.P. XIV, 1950.
(18) Wokes, F., *Quart. J. Pharm. Pharmacol.*, **11**, 521 (1938).

J. B. Lesh

ANTITHYROID SUBSTANCES

The antithyroid substances interfere with or depress the production or utilization of thyroid hormone in the body. Historically, large doses of iodide were used in the treatment of hyperthyroidism to depress thyroid function. More recently other more effective antithyroid drugs such as 1-methyl-2-mercaptoimidazole, thiouracil and its derivatives, and radioactive iodide have come into use.

The normal production of thyroid hormone is governed in a number of ways. The anterior lobe of the pituitary gland secretes a substance (thyrotropic hormone) (see Vol. **7**, p. 488) that stimulates the thyroid. In turn the production of this hormone is governed by the level of thyroid hormone in the blood. Thus, when the hormone level is low, the pituitary secretes larger quantities of thyrotropic hormone, which then stimulates the thyroid to produce more hormone. An idea has been advanced, although not well established, that after repeated administration of the thyrotropic hormone of the pituitary, the body may produce an antithyrotropic (thyroid-depressing) hormone (7).

The principal antithyroid drugs act to interfere with the metabolism of iodide and the formation of the iodinated amino acids (2) (see p. 128). In general, substances that possess antithyroid activity for animals are also active in man. A drug having a relatively low order of activity when tested in an animal, however, may be more active

TABLE I. Relative Activities of Antithyroid Agents.

Compound	Relative activity	
	Man	Rat
2-Thiouracil	1	1
6-Methyl-2-thiouracil	2	1
6-Propyl-2-thiouracil	0.75	11
2-Mercaptoimidazole	10	2
1-Methyl-2-mercaptoimidazole	100	2

in man and vice versa. Table I gives the relative activities of five of the more potent antithyroid agents in the rat and in man (15).

Iodide and Other Inorganic Ions

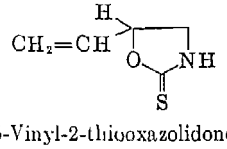
For the past 40 years, iodide has been used for the treatment of hyperthyroidism (9). When given in large doses, it depresses the functioning of the overactive thyroid gland. This depressing action of large quantities of iodide appears to be paradoxical, since iodide in small quantities is essential for the formation of thyroid hormone. The mechanism by which iodide ion in large quantity acts as an antithyroid agent is not known, although it has been the subject of much study and speculation (14). See also *Iodine preparations.*

Thiocyanate, first shown in 1936 to possess antithyroid properties, appears to act by depressing the ability of the thyroid gland to concentrate iodide from the blood stream. Other ions such as chlorate, perchlorate, iodate, and periodate have a similar activity (10). These substances are not used clinically because of toxic side effects.

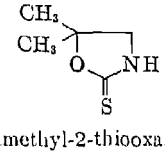
Radioactive Iodide (I^{130} and I^{131}). Since the radioactive isotopes I^{130} and particularly I^{131} have become available from the atomic pile, they have been used clinically to a limited extent to treat hyperthyroidism. When I^{131} is given by injection it becomes concentrated in the thyroid gland, and by virtue of its β-radiation destroys part of the tissue. Thus the administration of radioactive iodide has the same effect as surgical removal of part of the gland. The use of I^{131} requires special techniques and equipment and is considered somewhat dangerous.

Naturally Occurring Antithyroid Agents

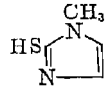
Antithyroid effects have been observed for some time in animals fed large quantities of certain plants of the cabbage and turnip families. One highly effective compound, *levo*-5-vinyl-2-thiooxazolidone (5-vinyl-2-oxazolidinethione), has been isolated from rutabaga, cabbage, turnip, and kale (4). 5,5-Dimethyl-2-thiooxazolidone (5,5-dimethyl-2-oxazolidinethione), isolated from the seeds of *Conringia orientalis* (11), also possesses antithyroid properties (3).



5-Vinyl-2-thiooxazolidone



5,5-Dimethyl-2-thiooxazolidone



1-Methyl-2-mercaptoimidazole

Organic Antithyroid Agents

In 1943, a number of organic compounds were discovered to possess antithyroid properties (5,13). Since that time many hundreds of compounds have been tested and numerous antithyroid agents have been found. These fall into two main classifications.

AROMATIC AMINES AND PHENOLS

Sulfanilamide, *p*-aminobenzoic acid, 1-naphthol, *p,p'*-diaminodiphenylmethane (4,4'-methylenedianiline) and hydroquinone are examples of this group. By far the

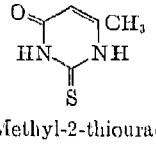
most active compounds of this group are phloroglucinol and resorcinol (8). These substances appear to act by combining with iodine in the gland in competition with tyrosine.

DERIVATIVES OF THIOUREA

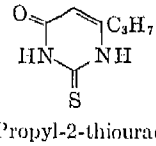
The derivatives of thiourea (see *Urea*) are considerably more potent antithyroid agents than the aromatic amines and phenols. All of the drugs now in use for the control of hyperthyroidism are thiourea derivatives. Thiourea itself and the *N*-substituted compounds like *N*,*N*,*N*′,*N*′-tetramethylthiourea are appreciably active. The most potent and useful antithyroid drugs, however, are the cyclic derivatives.

The four compounds described here are currently sold as drugs for the treatment of hyperthyroidism. They have largely displaced iodide for the treatment of severe hyperthyroidism, although mild forms of hyperthyroidism are still treated with iodine. At present, the preferred course of treatment is to give one of these drugs in multiple daily doses until the disease is controlled and then to continue treatment with smaller maintenance doses. Often, after the disease is well controlled, a thyroidectomy is performed. All of the drugs listed are capable of producing toxic symptoms such as granulocytopenia, leukopenia, drug fever, and dermatitis in some few patients. If such symptoms occur, the drug treatment must be immediately discontinued. The total market value of the synthetic antithyroid drugs listed here amounted to about $600,000 in 1953. There is no estimate of the quantity of iodide used for antithyroid purposes.

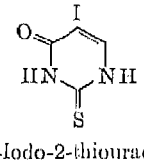
1-Methyl-2-mercaptoimidazole (Methimazole, N.N.R.), is a white crystalline solid, m.p. 145–48°C., and is soluble to the extent of about 1 g. in 4.5 ml. of water. It is obtained by the condensation of *N*-methylaminoacetal, $CH_3NHCH_2CH(OC_2H_5)_2$, with thiocyanic acid in aqueous solution (12). It is given by mouth in doses of 5–10 mg. three times a day for 30–60 days, or until the hyperthyroidism is controlled. A maintenance dose of 5–10 mg. per day is used to keep the disease under control.



6-Methyl-2-thiouracil



6-Propyl-2-thiouracil



5-Iodo-2-thiouracil

6-Methyl-2-thiouracil, N.N.R. (Methiacil, Muracil, Thimecil), is a white crystalline solid, m.p. 326–31°C. (decompn.), very slightly soluble in water. The preparation of this compound involves condensation of thiourea with ethyl acetoacetate (1). The dosage is about 200 mg. per day given orally.

6-Propyl-2-thiouracil, U.S.P. XIV, N.N.R., is a white crystalline solid, m.p. 218–20°C., very sparingly soluble in water. It is prepared by reaction of thiourea with ethyl butyrylacetate (1). The dosage is about 100–150 mg. per day orally.

5-Iodo-2-thiouracil is a white crystalline solid, m.p. 214–15°C. (decompn.). The preparation of this compound involves the iodination of 2-benzylthiouracil followed by debenzylation with hydrogen iodide (6). The recommended dose is about 300 mg. per day.

Methods of Testing

The original method of testing substances for antithyroid activity in animals (usually rats) consists of giving the substance to be tested, generally by feeding in the diet, for a period of days or weeks and then comparing the weights of the thyroid glands of the treated animals with those of normal animals. An antithyroid substance causes an increase in the weight of the thyroid gland; the more potent the drug, the greater is the weight increase (3).

A more precise method of testing, and one that can be applied to human patients, involves the use of trace amounts of radioactive iodide ion. The animal, or patient, is given a very small (nontoxic) quantity of I^{131} by injection. Normally this becomes concentrated in the thyroid gland, where it is incorporated into the hormone and can be detected there for many hours. If, however, the test subject has been treated previously with an antithyroid drug, a smaller amount of the injected I^{131} is concentrated and retained by the gland. The smaller the quantity of radioactivity that can be detected in the gland after a specified period of time, the more potent is the antithyroid substance being tested (15).

Bibliography for Antithyroid Substances

(1) Anderson, G. W., Halverstadt, I. F., Miller, W. H., and Roblin, R. O., *J. Am. Chem. Soc.*, **67**, 2197 (1945).
(2) Astwood, E. B., *Annals N.Y. Acad. Sci.*, **50**, 419 (1949).
(3) Astwood, E. B., Bissell, A., and Hughes, A. M., *Endocrinology*, **37**, 456 (1945).
(4) Astwood, E. B., Greer, M. A., and Ettlinger, M. G., *Science*, **109**, 631 (1949).
(5) Astwood, E. B., Sullivan, J., Bissell, A., and Tyslowitz, R., *Endocrinology*, **32**, 210 (1943).
(6) Barrett, H. W., Goodman, I., and Dittmer, K., *J. Am. Chem. Soc.*, **70**, 1753 (1948).
(7) Collip, J. B., and Anderson, E. M., *Lancet*, **1**, 76 (1934).
(8) Fawcett, D. M., and Kirkwood, S., *J. Biol. Chem.*, **204**, 787 (1953).
(9) Goodman, L., and Gilman, A., *The Pharmacological Basis of Therapeutics*, Macmillan, N.Y., 1941, pp. 1161–65.
(10) Gross, J., and Pitt-Rivers, R., "Recent Knowledge of the Thyroid Gland," in Harris, Marrian, and Thimann, *Vitamins and Hormones*, Academic Press, N.Y., 1953, Vol. XI, pp. 159–71.
(11) Hopkins, C. Y., *Can. J. Res.*, **B16**, 341 (1938).
(12) Jones, R. G., Kornfeld, E. C., McLaughlin, K. C., and Anderson, R. C., *J. Am. Chem. Soc.*, **71**, 4000 (1949).
(13) MacKenzie, C. G., and MacKenzie, J. B., *Endocrinology*, **32**, 185 (1943).
(14) Pitt-Rivers, R., *Physiol. Rev.*, **30**, 194 (1950).
(15) Stanley, M. M., and Astwood, E. B., *Endocrinology*, **44**, 588 (1949).

R. G. JONES

THYROTROPIC HORMONE. See *Hormones (anterior-pituitary)*, Vol. **7**, p. 488.

THYROXINE, THYROXIN. See *Amino acids*, Vol. **1**, p. 719, 726; *Thyroid and antithyroid preparations.*

TIGLOIDINE, $C_{13}H_{21}NO_2$. See *Alkaloids*, Vol. **1**, p. 480.

TIGONIN; TIGOGENIN, $C_{27}H_{44}O_3$. See *Saponins and sapogenins*, Vol. **12**, pp. 100, 104.

TILE. See *Asphalt tile*; *Ceramic industries*, Vol. **3**, p. 521.

TIN AND TIN ALLOYS

Tin, Sn, atomic number 50, atomic weight 118.70, is in Group IV of the periodic table and is a member of the subgroup containing germanium and lead. The valence number is +2 or +4. The ten naturally occurring isotopes, listed in the order of their abundance, are 120, 118, 116, 119, 117, 124, 122, 112, 114, and 115. Tin is present in the igneous rocks of the earth's crust to the extent of about 0.001%. Two allotropic forms exist: white tin (β) and gray tin (α). White tin crystallizes in the body-centered tetragonal system, and gray tin crystallizes in the cubic system. Although the transformation temperature is 13.2°C., the change into the gray form does not take place under practical conditions unless the metal is of high purity and is exposed to temperatures well below zero. Small amounts of bismuth, antimony, lead, silver, and gold in the tin retard the transformation. Thus, commercial grades of tin resist transformation because of the inhibiting effect of these elements present as impurities. Small amounts of aluminum and zinc are reported to accelerate the change (1). An expansion of 25% in volume accompanies the change from white to gray tin. The first signs of transformation are the appearance of gray spots and the formation of a powder. Gray tin is converted back to white tin by raising the temperature above 13.2°C.; it can be remelted to the white form without change in properties.

Tin is a nontoxic, soft, and pliable metal adaptable to all types of cold working such as rolling, extrusion, and spinning. It is readily joined with low-melting solders. It has a white silvery color with a bluish tinge and when highly polished has a high light reflectivity. It retains its brightness well during exposure both outdoors and indoors. Alloying elements such as copper, antimony, bismuth, and cadmium increase its hardness. The most important application is as a coating for steel (tinplate) which, in the form of the tin can, serves as the most efficient container for the preservation of perishable foods. It is alloyed with lead to produce solder; with antimony, copper, or lead to form babbitts, type metals, and casting alloys; and with copper to produce the various brasses and bronzes. Less important uses are for collapsible tubes, fusible alloys, decorative and corrosion-resistant alloy coatings, and chemical reagents and compounds. See also *Tin compounds*.

Evidence of the earliest use of tin dates back to the period between 3200 and 3500 B.C. Practically all the tin in the early period was procured from a group of islands known as the Cassiterides which may have been the Scilly Isles (southwest of Cornwall) or more likely Cornwall itself. Historical references to trade in tin became more evident after the Romans reached Cornwall. Production of tin in Cornwall in the 13th century amounted to about 300 tons, and by the 19th century it had reached 9,000 tons. Present production is less than 1,000 tons a year.

Mining in Malaya (now the world's largest producer) and China dates back to at least as early as the 9th century. Indonesia and Thailand started production in the early part of the 18th century. Production in Bolivia, the Belgian Congo, and Nigeria is comparatively recent.

Physical and Chemical Properties

Constants. The physical constants of tin are shown in Table I.

Reactions. Tin is amphoteric, reacting with both strong acids and strong bases, but it is relatively resistant to nearly neutral solutions. Oxygen greatly accelerates corrosion in aqueous solutions. In the absence of oxygen, the high hydrogen overpotential of tin causes a film of hydrogen to be retained on the surface so that attack by acids is retarded. The metal is normally covered with a thin invisible film of stannic oxide which may be completely removed by acids or alkalies.

TABLE I. Constants.

M.p., °C	231.9
B.p., °C	2270
Sp.gr.	
α-form (gray tin)	5.77[13]
β-form (white tin)	7.29[15]
Liquid at m.p.	6.97
Transformation temp. $\beta \rightleftharpoons \alpha$, °C	13.2
Vapor pressure, mm., at:	
1000°K.	7.4×10^{-6}
1300°K.	8.3×10^{-3}
1500°K.	0.17
2000°K.	30.6
2550°K.	638
Surface tension, dynes/cm.	
Solid tin at 215°C.	685
Liquid tin, 400–800°C.	$(700 \pm 25) - (0.17 \pm 0.015)T^{[a]}$
Viscosity, centipoises, at:	
250°C.	1.88
300°C.	1.66
400°C.	1.38
500°C.	1.18
800°C.	0.87
Sp.heat, cal./gram	
White tin at 25°C.	0.053
White tin, 25°C.–m.p.	$0.0372 + 0.053 \times 10^{-3}T^{[a]}$
Gray tin at 10°C.	0.049
Liquid tin, m.p.–1000°C.	0.0615
Latent heat of fusion, cal./gram	14.2
Latent heat of vaporization, cal./gram	520 ± 20
Heat of transformation, cal./gram	4.2
Energy of activation, cal./gram	
White→gray	1.5
Gray→white	19.4
Thermal conductivity, cal./(sec.)(sq.cm.)(°C./cm.)	
White tin at −170°C.	0.193
White tin at 0°C.	0.150
White tin at 100°C.	0.145
White tin at 200°C.	0.135
Liquid tin, m.p. to 332°C.	0.078
Coefficient of linear expansion, at:	
0°C.	19.9×10^{-6}
100°C.	23.8×10^{-6}
Shrinkage on solidification, %	2.8
Resistivity of white tin, microhms/cm. cube, at:	
0°C.	11.0
100°C.	15.5
200°C.	20.0
M.p. (solid)	22.0
M.p. (liquid)	45.0
400°C. (liquid)	49.0
Volume conductivity, I.A.C.S. (see Vol. 4, p. 432)	15
Magnetic susceptibility, c.g.s. units	
White tin at 18°C.	0.027×10^{-6}
Gray tin at 0°C.	-0.031×10^{-6}
Liquid tin at 250°C.	-0.036×10^{-6}

(Continued)

TABLE I. Constants (*Concluded*).

Brinell hardness, 10 kg./5 mm./180 sec., at:	
20°C.	3.9
220°C.	0.7
Tensile strength as cast, p.s.i., at:	
15°C.	2,100
200°C.	650
−40°C.	2,900
−120°C.	12,700

[a] T in °K.

Halogen acids attack tin particularly when hot and concentrated. Hot sulfuric acid will dissolve the metal, especially in the presence of oxidizing agents. Nitric acid attacks tin slowly when cold and dilute, more rapidly with rising temperature and concentration. Hot nitric acid converts the tin to metastannic acid (hydrated stannic oxide) (see p. 161). Oxalic acid is probably the most corrosive of the common organic acids toward tin.

Dilute solutions of weak alkalies, such as ammonium hydroxide and sodium carbonate, have little effect on tin, but a strong alkali, such as sodium hydroxide, is corrosive when cold and in dilute solution. Strong alkalies dissolve tin with the formation of stannates.

Salts with acid reaction in solution, such as aluminum chloride, attack tin in the presence of oxidizers or air. Ferric chloride solutions attack tin, particularly in the presence of air or oxygen. Nonaqueous mediums have little effect on tin.

The oxidation-reduction potentials are as follows:

$$Sn \longrightarrow Sn^{2+} + 2\,e^- \qquad \Delta E^\circ = +0.14 \text{ v.}$$

$$Sn^{2+} \longrightarrow Sn^{4+} + 2\,e^- \qquad \Delta E^\circ = -0.15 \text{ v.}$$

$$Sn + 3\,OH^- \longrightarrow HSnO_2^- + H_2O + 2\,e^- \qquad \Delta E^\circ = +0.79 \text{ v.}$$

Analysis

Tin in solution can be detected by the formation of a white precipitate with mercuric chloride. Stannous tin in solution gives a red precipitate with toluene-3,4-dithiol (Dithiol).

Tin metal is obtainable commercially in a high state of purity. Grade A metal is guaranteed to contain a minimum of 99.80% tin. Except for special purposes, the user rarely needs to know the amounts of the different impurities. However, photometric, chemical, and spectrographic methods are available for the determination of impurities in tin.

The most satisfactory gravimetric method is based on the precipitation of the tin-tannin complex from solutions of controlled acidity, and subsequent ignition of the complex to SnO_2. This procedure gives a precipitate which, unlike metastannic acid, is readily filtered and is free from occlusions after one precipitation.

Volumetric methods are based upon the reducing power of stannous compounds. Tin or tin alloy is put in solution with hydrochloric acid, reduced by digesting with a nickel coil, iron wire, or other reductant, cooled in a protecting atmosphere of carbon dioxide, and titrated with a standard iodine or iodate solution. The reaction involved is:

$$SnCl_2 + I_2 + 2\,HCl \longrightarrow SnCl_4 + 2\,HI$$

For the estimation of a high tin content, care is needed in standardizing the iodine solution against a reference sample of tin. Accuracy may be increased by taking a large sample (5 g.). A weighed amount of solid iodate is added to react with the major portion of the tin chloride, and the titration is finished with a standard solution of iodate as usual (14).

The determination of the impurities in pure tin may be conveniently carried out if the tin is first removed by volatilization of the bromide. Photometric methods for arsenic, antimony, lead, copper, bismuth, iron, nickel, cobalt, aluminum, cadmium, sulfur, and zinc are sufficiently sensitive to allow use of quite small samples. Spectrographic tin metal standards in the range of 99.11–99.95% tin are available from the National Bureau of Standards.

Occurrence

There are four important tin-producing areas in the world. Southeastern Asia is by far the most important of these. The chief tin-bearing belt of this region extends from Rangoon through the Isthmus of Kra and the Malayan Peninsula to the islands of Bangka and Billiton. To the north on the periphery of this belt are the fields of central Burma, French Indo-China, and China. This area supplied 61% of the world mine production in 1953 (177,500 long tons of tin in concentrates). Four principal producing countries in this area account for over 99% of its production. Tin production (in long tons) in these countries for 1953 was as follows:

Malaya	56,255
Indonesia (Bangka, Billiton, and Singkep)	33,753
Thailand	10,124 (estd.)
China	6,300 (estd.)

The other major tin-producing countries are Bolivia, the Belgian Congo, and Nigeria. Production (in long tons) of tin in concentrates from these countries in 1953 was as follows:

Bolivia	34,836 (19.6% of 1953 world production)
Belgian Congo	17,153 (9.7% of 1953 world production)
Nigeria	8,222 (4.6% of 1953 world production)

Bolivia with about 20% of world production has long been the second-largest tin-producing country, but in some recent years it was supplanted in this position by Indonesia. Bolivia also has the distinction of being the only important producing area in which practically all the tin produced is mined from primary deposits in hard rock, that is, from lode deposits. In all the other important tin-producing areas, deposits of secondary origin, placer deposits, are the principal sources of tin. These secondary deposits account for two-thirds of world production.

Of the nine different tin-bearing minerals found in the earth's crust, only one, *cassiterite* ("tinstone"), SnO_2, is of commercial importance. All the other minerals are complex sulfides and are significant only in Bolivia. *Stannite*, Cu_2FeSnS_4 and teallite, $Pb(Zn)SnS_2$, are the most important of these.

In all lode deposits, cassiterite is always found closely associated with granitic rocks such as granite, granodiorite, quartz-mouazite, and related porphyries and pegmatites. The granitic intrusions are considered to be the source of tin mineralization, yet only a few of the granite areas of the world have yielded minable deposits of tin. Placer deposits are formed by surface geological action (weathering and usually

erosion) on lode deposits. They exist in three varieties, depending on the amount of water erosion the deposit receives, the amount of chemical weathering being about the same in each case. These are: (*1*) residual concentrations, (*2*) eluvial deposits, and (*3*) alluvial deposits.

Mining and Concentration

Mining methods for tin ore depend on the character of the deposits. Five methods are used: dredging, gravel-pump mining, hydraulicking, open-cut mining, and underground mining. Of these, dredging, gravel-pump mining, and underground mining are most productive.

Dredging is mining with a floating dredge usually on an artificial pond in a placer. Preliminary roughing and cleaning are done with jigs and shaking tables on board the dredge. Final concentration is done in the cleaning shed on shore. The dredges in Malaya operate on tin ore averaging 0.3 lb. of tin metal per cubic yard. Final shed concentrates contain between 70 and 77% tin, that is, almost pure cassiterite (78.6% tin).

Gravel-pump mining, the second most important mining method, is widely used in small-scale placer operations in southeast Asia. Essentially, the method consists of elevating tin ore to a concentrating sluice box from a sump dug in the placer.

Underground mining is important only in Bolivia. In the other principal mining areas, only a few lode deposits have been mined. Underground lode deposits in Bolivia are located at very high altitude, 12,000–15,000 ft. above sea level. Access to these lodes is by the usual method of shaft sinking and by driving adits (entrances) depending on the terrain. Underground excavation is by means of stopes, the ore being broken from the working face by blasting and drilling. The Bolivian deposits are low grade, being deposited in narrow veins, and complex, being mixed with other minerals of copper, lead, bismuth, arsenic, sulfur, and in some instances tungsten. Such deposits require costly mining and concentrating systems. This, together with high transportation costs, make Bolivia the highest-cost major producer.

Smelting

PREPARATION OF ORE FOR SMELTING

Tin is easily reduced from cassiterite by heating at high temperatures with carbon. Concentrates from those alluvial deposits that are almost pure cassiterite with only traces of other reducible metallic impurities can be smelted directly. Others, particularly vein deposits such as those from Bolivia, require extensive preparation before smelting to get rid of associated impurities. Gravity concentration of these ores may yield a concentrate containing, besides cassiterite and earthy diluents, tungsten, iron, copper, arsenic, lead, antimony, nickel, zinc, bismuth, and silver, mainly as sulfides. Arsenic is often in the form of arsenides or arsenates of iron or other metals. Tungsten, when present, is usually in the form of tungstates of calcium or of iron and other metals.

Roasting will remove most of the sulfur and arsenic in the form of sulfur dioxide and arsenic oxides; the sulfides of iron, copper, bismuth, and zinc are converted to oxides; and lead sulfide is oxidized to sulfate. Roasting in firebrick-lined rotating cylinder-type furnaces is most popular. Next most popular is roasting in the fixed-hearth, revolving-rabble type of furnaces having either multiple hearths one above the

other or, in some cases, a single hearth. Some ores are hand-rabbled in a reverberatory furnace. Cassiterite is not appreciably altered by roasting, but many of the minerals associated with it are so altered that further mechanical separation is possible. The roasted concentrates are leached with dilute acid to remove the oxides of bismuth, zinc, and copper; tungsten may be removed by heating with sodium carbonate or sodium sulfate followed by leaching with water. Lead, antimony, silver, and bismuth may be removed by a chloridizing roast, followed by leaching with acid. Practically all of the metal sulfide minerals can be removed by oil flotation, but this method has not been extensively used. Selections of combinations of these methods of removing various impurities depend, of course, on the extent and variety present.

The main tin smelters of the world are shown in Table II.

TABLE II. Main Tin Smelters.

(Over 5,000 Tons Capacity)

Smelters	Est. annual capacity, long tons	Est. 1953 tin metal production
U.S.		
Tin Processing Corp., Texas City, Tex.	45,000	37,700
Europe		
Belgium: Société Générale Métallurgique de Hoboken S.A., Hoboken	18,000	9,000
Netherlands: N.V. Hollandsche Metallurgische Bedrijven, Arnhem	60,000	27,000
United Kingdom (29,000 tons total): Williams Harvey and Co. Ltd., Bootle	>5,000	Not pub.
Asia		
China: Yunnan Tin Corp., Kochiu, Yunnan	Not pub.	6,300
Indonesia: Indonesian Government Undertaking Bankatinwinning, Muntok (Banka)	10,000	Not prod.
Malaya: Eastern Smelting Co. Ltd., Penang	Not pub.	Combined prod. about 60,000 tons
Straits Trading Co. Ltd., Palau Brani (Singapore)	Not pub.	
Africa		
Belgian Congo: Compagnie Géologique et Minière des Ingénieurs et Industriels Belges Géomines, Manono, Katanga	7,000	2,700

ORE SMELTING

While the metallurgy of tin is comparatively simple, there are several complicating factors that must be dealt with in tin smelting practice. These are: (*1*) The temperature necessary for the reduction of tin dioxide with carbon is high enough to reduce the oxides of other metals which may be present. Reduced iron forms hard compounds with tin, the "hard head" of the tin smelter. (*2*) Tin at smelting temperatures is more fluid than mercury at room temperature. It finds the most minute openings for escape and soaks into porous refractories. (*3*) Tin oxide is amphoteric and reacts with either acid or basic furnace linings. Thus the slags produced contain appreciable quantities of tin and require further treatment.

Chiefly because of the loss of tin in the slag, the smelting of tin includes three stages: (*1*) The primary smelting of tin concentrates in a blast furnace, reverberatory,

or electric air furnace; (*2*) the retreatment of first run slags to recover tin; and (*3*) the refining of the reduced metallic tin to remove the metal impurities.

Blast- or shaft-furnace smelting is the oldest method of smelting tin. Some hand-operated shaft furnaces are still used in the Far East. However, modern water-jacketed blast furnaces, similar to the modern lead blast furnace (see Vol. 8, p. 229), but having a lower shaft, are in general use where tin concentrates are smelted in shaft furnaces.

In the blast furnaces used for the smelting of tin concentrates, coke is used as fuel and limestone, silica, and other materials as fluxes to produce easily fusible slags. The chief difference between tin smelting and the smelting of other metals is in the

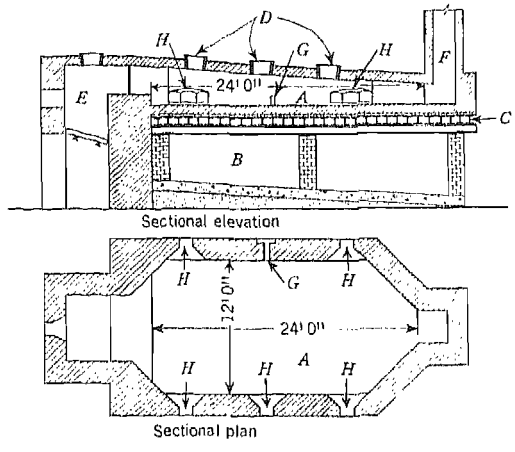


Fig. 1. Tin reverberatory furnace (5).

A. Hearth.
B. Open space below hearth for recovery of tin which penetrated hearth.
C. I beams supporting brick hearth.
D. Charge holes in roof.
E. Firebox.
F. Flue.
G. Taphole.
H. Working (rabbling) door.

tin content of the first-run slags obtained in tin smelting. The formation of tin silicates causes economic difficulties, but the silicates of tin have low melting points and thus do not hinder the satisfactory operation of the furnaces. Slags made in blast furnaces which smelt tin concentrates in ordinary practice may contain 10–25% tin.

A brick-lined settler or forehearth sometimes is used to collect the slag and tin from the blast furnace. The slag usually overflows from the settler into slag pots from which the molten slag is poured into water in order to granulate it. Alternatively, the slag may be removed after solidification and broken up for recovery of the tin. The metallic tin is periodically tapped from the bottom of the settler into cast-iron molds. The pigs or slabs of tin are removed from the molds for refining.

Most of the large modern tin smelting plants use **reverberatory furnaces** for both the smelting of primary tin concentrates and the retreatment of first-run slags to remove the tin they contain. Reverberatory furnaces have advantages over blast furnaces in smelting tin. The operations are more easily controlled; cleaner slags are produced, and reverberatory furnaces are more suited to the smelting of finely divided ores and concentrates, since the loss of tin as dust is much smaller. This is important

in tin smelting, owing to the high cost of the metal. Dust collecting equipment is necessary for successful operation. Figure 1 is a sketch of a tin smelting furnace. Figure 1 shows the firebrick hearth sloping toward the taphole, which is near the center of one side, and is low enough to drain the furnace completely when the taphole is open. Also shown are the arched roof, and the charge holes at regular intervals down the center of the furnace roof. Feed bins of the charge are, in some furnaces, kept above the charge holes. The roof is supported by steel beams to prevent damage to the side walls endangering the roof. The furnaces are of firebrick, and vary in size, the largest having a hearth of about 30–40 ft. long and 12–15 ft. wide. Coal is the most commonly used fuel, although fuel oil is an excellent fuel if the cost is not excessive. The larger furnaces will take a charge of 8–15 tons, the charge containing tin concentrates, 15–20% anthracite, and smaller amounts of limestone, slag, sand, and by-products from the refining of tin.

After thorough mixing, the charge is added to the furnace. Tin smelting is a batch operation, one charge being smelted and tapped before the next is added. The furnaces are operated at 1200–1300°C., and the time for each charge is 10–12 hours in the larger furnaces. The charge should be thoroughly stirred at intervals during smelting. In order to minimize the amount of impurities in the tin, considerable tin is allowed to leave as slag, since otherwise excessive amounts of impurities, as well as iron-tin alloy, would be present in the reduced tin.

The completed batch is tapped into a settler, from which the slag usually overflows into cast iron pots. The slag can be removed from these pots by immersing iron bars in the molten slag and lifting the slag by means of the bars after it has cooled and solidified. The slag, usually containing about 10–25% tin, is crushed to ¾ in. diameter lumps for resmelting. The molten tin from the bottom of the settler is cast into slabs or pigs, of about 75 lb. The slabs are preferred, since they are more suitable for charges in the refining furnaces. Since the next charge should be melted as quickly as possible to reduce the tin rapidly, it is added immediately to the furnace after the furnace has been tapped.

In addition to the use of blast furnaces and reverberatory furnaces, smelting is also carried out in modern three-phase Heroult *electric arc furnaces*.

SLAG SMELTING

The resmelting of slag to recover tin is carried out in the same type of furnace used for smelting the ore concentrate, but a higher temperature, up to 1480°C., is necessary with slag, since the reduction of tin from the silicates found in the slag is more difficult than the reduction of the oxides of the ore. Anthracite screenings are usually used as a reducing agent, and fairly large amounts are required. In addition, limestone is usually added as a flux, and either metallic iron or lime may be added to replace tin in the tin silicates, thus aiding the reduction to tin metal. Although slags should not contain more than 1% tin after they are smelted, they frequently contain more than this, many containing more than 3% being discarded.

Refining

Both the tin obtained by smelting ore concentrates and that obtained by smelting slags contain sufficient impurities that they must be refined before marketing. This refining may be by either heat treatment or electrolytic processes, although heat

TABLE III. Brands of Tin.

Brand	Sn	Sb	As	Pb	Bi	Cu	Fe	Ag	S	Ni and Co	Cd
American											
U.S. Spec. (Gr. AA)	99.95[a]	0.02[b]	0.01[b]	0.02[b]	0.01[b]	0.02[b]	0.01[b]	—	—	—	0.001[b]
G. S. A. Federal Supply Service Spec. P-55[c]	99.80[a]	0.04[b]	0.05[b]	0.05[b]	0.015[b]	0.04[b]	0.015[b]	—	0.01[b]	0.01[b]	0.001[b]
Longhorn 3-Star	99.86	0.031	0.024	0.040	0.004	0.030	0.001	—	0.002	0.003	Nil
M. & T. electrolytic	99.98	0.007	Trace	0.008	Trace	0.001	0.006	[d]	[d]	[d]	[d]
M. & T. No. 1	99.96	0.007	0.016	0.010	Trace	0.001	0.007	[d]	[d]	[d]	[d]
Vulcan electrolytic	99.9908	0.0041	Trace	0.0009	0.0002	0.0002	0.0038	Trace	Nil	Nil	Nil
Vulcan American	99.9810	0.0016	0.0029	0.007	0.0005	0.0035	0.003	Trace	Nil	0.0005	Nil
English											
Pass No. 1	99.991	0.0048	0.0003	0.0011	0.0001	0.0003	0.0026	—	0.0001	—	—
Chempur	99.992	0.0034	0.0001	0.0032	0.0002	0.0002	0.0004	—	0.0002	—	—
Cornish refined	99.820	0.022	0.030	0.065	0.010	0.034	0.005	Nil	Nil	0.014	Nil
Hawthorne refined	99.891	0.010	0.029	0.028	0.004	0.028	0.010	Nil	Nil	Trace	Nil
Mellanear L. & F. (com.)	99.169	0.046	0.071	0.362	0.027	0.304	0.008	0.002	Nil	0.011	Nil
Mellanear refined	99.827	0.028	0.025	0.065	0.013	0.022	0.005	0.002	Nil	0.013	Nil
Mellanear (guar. 99.9%)	99.915	0.013	0.008	0.037	0.007	0.009	0.004	Nil	Nil	0.007	Nil
Straits											
E. S. Coy (Penang)	99.899	0.004	0.031	0.030	0.011	0.012	0.006	Nil	0.002	0.005	Nil
Straits Trading (Sing.)	99.895	0.004	0.031	0.029	0.007	0.025	0.009	Nil	Nil	Trace	Nil
Indonesian											
Banka	99.935	0.004	0.014	0.033	0.001	0.006	0.007	—	—	—	—
Dutch											
Billiton	99.935	0.004	0.013	0.034	0.001	0.006	0.007	Nil	Nil	Nil	Nil
Tulip	99.874	0.010	0.008	0.086	0.001	0.010	0.011	Nil	Nil	Nil	Nil
Dutch L. & F.	99.128	0.035	0.029	0.763	0.002	0.030	0.013	Nil	Nil	Nil	Nil
Belgian											
Katanga	99.966	Nil	0.006	0.012	Trace	0.013	0.003	Nil	Nil	Nil	Nil

[a] Minimum.
[b] Maximum.
[c] Zn, 0.005 maximum.
[d] Absent or in traces only.
Source: reference (8).

treatment is by far the most important. Heat treatment includes two steps: liquating, or sweating; and boiling (poling) or tossing. Either or both of these operations may be necessary. *Liquating* is always the first operation in the sequence. In liquation, tin is heated in a small reverberatory furnace to just above its melting point. By this means, metals whose melting points are sufficiently higher than that of tin are separated from the tin, since the impurity remains in the dross. Thus iron is largely removed. Lead and bismuth remain in the tin, but arsenic, antimony, and copper are partly removed by remaining in the dross.

Boiling and tossing are operations in which molten tin is heated while being agitated. The action of atmospheric oxygen causes metallic impurities to form lighter compounds, which come to the surface of the molten metal, and thus can be removed. These scums can be resmelted along with ore concentrates to recover their tin content. In *boiling*, the molten tin is stirred with sticks of green wood. These are decomposed by the heating to give an evolution of gas, which stirs the liquid. In *tossing*, the molten metal is poured from ladles into the heating kettle. After refining the tin is cast into pigs.

Electrolytic refining produces a much purer grade of tin than heat treatment, and has been used successfully in the U.S. However, it has been little used, since there is no extensive market for this purer grade.

Specifications and Standards

Before World War II, tin was for the most part sold under brand names based on the company producing the tin, the name of the smelter, or the region in which the ore was produced. Table III presents the various brands of tin found most commonly in the U.S. markets and their average analyses. During World War II, the U.S. Government Agencies began utilizing a grading system for identifying the various types of tin. This grading system has been retained and is encountered in American price quotations. The grades established are shown in Table III. Other grades are: grade B—99.80% tin or higher but not meeting specifications for grade A (arsenic must not exceed 0.05%); grade C—99.65-99.79% tin or higher not meeting specifications for grade A or B (usually lead); grade D—99.50-99.64% (Longhorn 2-Star may contain 0.22% lead, other impurities fairly low); grade E—99.0-99.49% (Longhorn 1-Star may contain 0.76% lead, other impurities about twice that allowed in grade A).

Health and Safety

The small amounts of tin present in modern canned foods of good quality are quite harmless, but tin has a toxic action when administered in larger quantities, and some organic compounds are much more toxic than the simple salts. (See Vol. **9**, p. 635.) The agreed limit of tin content in foods is 300 mg. per kilogram in the U.S., and 286 p.p.m. in the United Kingdom. Tests have shown that many times these concentrations can be consumed without adverse effects on the human system.

The introduction of lead in terne coatings or in tin-lead solders requires the usual careful handling that is associated with lead (*q.v.*). Canned foods in tin-plated containers are soldered only on the outside of the doubly-folded body seam. Thus, the solder does not come into contact with the interior of the can. Where a seam must be exposed to food products, pure tin, tin-silver or tin-antimony alloys are available as alternatives to the tin-lead range of solders.

Economic Aspects

Tin is the most expensive of the common metals. The annual average prices of tin on the New York Market for the years 1950–1953 were as follows:

1950	1951	1952	1953
95.56¢/lb.	128.31¢/lb.	120.44¢/lb.	95.77¢/lb.

Because it is relatively expensive, tin finds use only where no other common metal will suffice. Table IV shows the important end uses for tin.

TABLE IV. Per Cent Consumption of Primary Tin by End Use in the U.S. and United Kingdom in 1953.

End use	U.S.	U.K.
Tinplate	57.5	47.8
Solder	19.8	8.9
Copper alloys (bronzes and brasses)	7.1	10.7
White metals (babbitts, etc.)	4.4	17.5
Tinning	4.7	6.9
Collapsible tubes and foil	1.7	3.0
Other	4.7	5.1

The U.S. is by far the largest consumer of tin. It used over 40% of the tin consumed in 1953. Seventeen other countries consumed more than 1,000 long tons per year. See Table V.

TABLE V. World Consumption of Tin.

Country	Consumption, long tons	% of world total
North America		
U.S.	53,961	40.5
Canada	3,950	3.0
South America		
Brazil	1,500	1.2
Argentina	1,200	0.9
Europe		
U.K.	18,634	14.3
France	7,370	5.7
Western Germany	5,814	4.5
Netherlands	4,330	3.3
Italy	2,780	2.1
Denmark	2,650	2.0
Poland	1,920	1.5
Czechoslovakia	1,800	1.4
Eastern Germany	1,500	1.2
Belgium and Luxembourg	1,174	0.9
Asia		
Japan	4,650	3.6
India	2,507	1.9
China	1,902	1.5
Australia	2,350	1.8
Total world consumption	130,000	

Uses

Tin is the most important metal that is not mined commercially in North America. Uses for tin are many and are probably more widespread than for any other metal. Tin finds its main outlet as a protective coating for stronger materials. Next important outlet is as an alloying element with a wide variety of other metals.

The ease with which tin flows under pressure makes it ideal for the manufacture of collapsible tubes and pipes. Tin pipe is used mostly for handling carbonated beverages and foods.

The use of tin for collapsible tubes is not nearly as important currently (1954) in the U.S. as it was before World War II. War-time restrictions forced the collapsible tube industry to replace the tin with aluminum, lead, and tin-coated lead. The favored tin alloy for collapsible tubes contains 0.25% copper to secure the optimum degree of strength and collapsibility. This alloy more closely approaches the ideal collapsible tube alloy than any of its replacements. It is perfectly collapsible and nontoxic; whereas aluminum work-hardens and lead is toxic. However, it is more expensive than the replacements and is used only in exacting applications.

Tin powder is used for metallizing for decorative paper, and in paste form for joining metals.

Tin coatings for copper, steel, and other metals are important outlets for tin, but the major one is tinplate for cans. From one-third to one-half of the tin used in the U.S. is used for tinplate. Large tonnages of steel are also used in tinplate. Tinplate accounted for 1 ton out of every 16 tons of steel produced in the U.S. in 1953. It is second only to the automobile industry as a major consumer of steel.

Roughly two-thirds of the cans manufactured in 1953 were food cans. Since linings of steel food cans must be both nontoxic and protective, tin is admirably suited for this job. Tin is more resistant than steel to atmospheric conditions. In the absence of air (in acid solutions), it protects steel even when the coating is imperfect. In the absence of air, the reversal of potential causes the tin to act as an anode, thus protecting the breaks in the coating. This unique property has been the keystone of the canning industry since its beginning in 1810 when Hall and Donkin, following Appert's directions for preserving, first produced canned foods in tinned-iron containers. As one might expect from the nature of this protection, the corrosion resistance is a direct function of the amount of tin present on the inside of the can.

The canning industry requires that canned foods withstand two years on the grocer's shelves. Before World War II, this requirement was easily met in all but the most corrosive food packs by using hot dip "standard coke tinplate," which averaged 80 millionths of an inch of tin on a side. With the Far Eastern tin fields cut off during World War II, it was necessary to stretch the tin supply as much as possible. Savings possible with the hot dip process were only 10–15%, owing to the limitations of the process. Accordingly, electrotinning processes, which could produce coatings of any thickness, were adopted. In 1953, 72% of the tinplate produced in the U.S. was electrotinned. (See Vol. **5**, p. 639.)

Electrotinplate is now produced in three standard coating thicknesses as follows: No. 25 (0.25 lb. of tin per base box) equivalent to 15 millionths of an inch, No. 50 (0.50 lb. of tin per base box) equivalent to 30 millionths of an inch, No. 75 (0.75 lb. of tin per base box) equivalent to 45 millionths of an inch.

The minimum coating weights of hot-dip tinplate, the so-called Common Cokes of commerce (1.25 lb. per base box calculated on a basis of pot yield) carry 70

millionths of an inch of tin on a side. Electrotinplate in the thinner coating weights is used in dry packs. It is also used for ends in mildly corrosive food packs. Some of the food packs require organic coatings over the tin to prevent either discoloration, bleaching, or off-flavor. A recent innovation is the so-called "differentially" coated electrotinplate. A different thickness of tin is applied to each side of the sheet, for example, the inside is coated with 60 millionths (1 lb. per base box) and the outside may be as low as 15 (0.25 lb. per base box) millionths of an inch of tin. Heavily tinned coatings of the order of 0.0005-0.0010 inch thick are applied to steel, cast iron, and copper articles that come into contact with foods. Examples are 5-gallon and 10-gallon tinned-steel milk cans, tinned cast-iron food grinders, and tinned-copper utensils used in restaurants and in food processing. The coatings are usually applied by hot dipping. A considerable amount of copper wire is tinned to prevent attack of the copper by rubber insulation and to make soldering easier. Steel, copper, and brass connectors used in the electrical industries are usually tinned to facilitate soldering.

Tin finds use in the so-called "fusible" alloys. See *Bismuth and bismuth alloys.*

Alloys

Coatings. *Terne plate,* the oldest tin alloy coating, is sheet steel covered with a tin-lead alloy by hot dipping. See Vol. 8, p. 905. It was first used as roofing material. Many other uses for terne plate since have been developed, so that now perhaps 40% of the tin-lead coated steel is used in other ways. Automobile gasoline tanks and exhaust pipes, for example, are terne-coated for added protection. Capacitor cans and transformer cans account for a considerable consumption of "terne" alloys for coatings. Terne-coating alloys contain from 12 to 50% tin. The higher tin contents are used where good soldering properties are desired.

Tin-alloy electrocoatings have been developed recently for a number of industrial applications. Seven alloy combinations are being used commercially. These are tin-copper, tin-zinc, tin-cadmium, tin-nickel, tin-lead, copper-tin-lead, and copper-tin-zinc.

The *tin-copper* electrocoatings fall into two classes: the lower tin content "red bronzes" which correspond to the ordinary copper-tin foundry alloys, and the higher tin content "white bronzes" or speculum alloys.

The red bronze coatings contain from 5 to 20% tin. They are used principally as a stop-off in nitriding and carbonitriding steel. They also provide an excellent corrosion-resistant undercoat for chromium plating.

Speculum alloy coatings contain 30–45% tin. They are hard and scratch-resistant and resist tarnishing by most food products. The alloy has a pleasing white color and is suitable for applications similar to those of silver plate. Two plating methods have been developed; one is bright as plated and the other requires some buffing to attain a high polish.

The outstanding characteristic of *tin-zinc* alloy coatings is the excellent protection afforded to steel. For the same thickness, tin-zinc provides greater protection than either zinc or cadmium. Like cadmium, it is easy to solder. The alloy is protective in the range 50–80% tin, the protective value increasing slightly with increasing tin up to 80%. Solderability is excellent for the 80% alloy and deteriorates steadily with reduction in tin content. These properties make the 80% alloy useful in the radio and television industry as a coating for chassis, loud-speaker frames, and other com-

ponents. If desired, the corrosion resistance can be further increased by a simple passivation treatment in hot 2% chromic acid solution.

Commercial methods for electroplating *cadmium-tin* alloy have been announced recently. Salt-spray and humidity-chamber test data show that alloys around 75% cadmium and 25% tin have many times the protective value of cadmium in affording corrosion protection for steel. This alloy is being used on aircraft-engine parts.

Until the recent announcement of a new method of electroplating bright *tin-nickel* coatings, electroplated chromium on a copper-nickel undercoat was the only known base-metal coating possessing a high degree of resistance to atmospheric tarnishing. The new tin-nickel coating method yields a bright 65% tin, 35% nickel alloy coating over a wide range of plating conditions in a singularly uncomplicated plating operation. This alloy coating is as lasting as chromium on nickel-copper. It has a pleasing color. Whereas chromium deposits have a bluish tint and nickel deposits a yellow tint, the tin-nickel deposits have a slight rose cast.

Electroplated *tin-lead* alloy coatings are a fairly recent development. They may be plated in any desired ratio, depending on the application. There are a considerable number of commercial installations. Coatings for the corrosion protection of bearing alloys are an important application.

Another recent commercial development that stemmed from tin-lead alloy plating is the use of *copper-tin-lead* electroplates in bearings. A method for electroplating a bright alloy deposit containing approximately 56% of copper, 28% of tin, and 16% of zinc was developed for military use during World War II. The coating has good wear and tarnish resistance and has been used to protect copper and copper alloys. Copper undercoats are necessary to secure satisfactory corrosion protection on steel.

Electrotin coatings containing small quantities of *bismuth*, of the order of 0.05–0.1%, have been advocated for low-temperature applications, to insure that no transformation of the "white tin" coatings to "gray tin" takes place. This transformation is accompanied by an expansion that disintegrates the tin coating into powder. Since bismuth is a potent inhibitor of this transformation, methods of plating small amounts of bismuth with tin have been tried experimentally.

Bronzes. The earliest known application of tin was as an addition to copper to harden it. These copper-tin alloys, with or without other modifying elements, are classed under the general name of tin bronzes. These include two principal types: the so-called *phosphor bronzes*, containing up to 10–12% tin with small additions of phosphorus added chiefly for deoxidation purposes; and the *gun metals*, which are tin bronze casting alloys modified with 1–6% zinc to secure gas-free, pressure-tight, corrosion-resistant castings. Both these alloy types may be further modified with additions of lead to secure better machinability and, in the case of phosphor bronzes, to secure a more conformable bearing alloy. There are some special alloys which fall outside these two principal types of tin-bronzes. *Bell metal*, for example, contains around 20% tin. However, these special alloys are not of great importance commercially. See *Copper alloys*.

Tin-Antimony-Copper Alloys. Tin requires both copper and antimony additions for satisfactory bearing properties. Up to 8.5% of each is used. Antimony strengthens the bearing alloy matrix by dissolving in tin up to about 8%. Above this, hard cubic particles of tin-antimony compound are formed which tend to float. Copper additions are necessary to secure a uniform distribution of these hard cubic particles. It does this by forming hard, needle-shaped, particles of copper-tin compound which

entrains the tin-antimony cubes, thus providing a relatively hard "pavement" in a soft but reasonably rigid bearing alloy matrix—the classic bearing alloy structure. See *Antimony and antimony alloys*; *Bearing metals.*

There are two other important end uses for these high tin-antimony-copper alloys; *die-casting alloys* and *pewter.*

Compositions of the three A.S.T.M. standard tin-base alloys for die casting are given in Table VI.

TABLE VI. Desired Compositions of A.S.T.M. Standard Tin-Base Die-Casting Alloys.[a]

Alloy No.	Composition, %			
	Tin	Antimony	Copper	Lead
1	91	4.5	4.5	—
2	82	13	5	—
3	65	15	2	18

[a] A.S.T.M. Standard B102-48.

The original pewters were alloys of tin and lead, but toxicity and dullness imparted by lead has precluded their use in modern pewter alloys. A range of composition for typical modern pewter that finds favor with many pewter craftsmen manufacturing artware contains 4–6.5% of antimony, 1–1.5% of copper, and the balance tin. A slightly harder alloy, *Britannia metal*, contains around 7% of antimony, 2% of copper, and the balance tin. This is used for such things as mountings on holloware which are subsequently silver plated. Pewter alloys for artware may be cast or spun. A recent development that avoids distortion in service, a serious drawback of ordinary pewter alloys, is a hardenable pewter. This alloy contains 0.1% of silver in addition to the usual proportions of antimony and copper. It is harder than ordinary pewter in the as-cast form but softens during rolling into sheet, so that it can be spun or hammered and then fully hardened by heat treatment. Up to 1.5% bismuth may be used as a hardener for cast pewter, but may cause brittleness in the spinning operation if lead impurities are present.

Lead-Antimony-Tin Alloys. Lead-base alloys containing tin and antimony are used extensively as a replacement for tin-babbitts. These so-called "lead babbitts" have been known for centuries in the form of type metals (*q.v.*). See also *Bearing metals*; *Lead alloys.* The particular compositions used in lead babbitts correspond to the harder type-metal alloys. There are two classes: (*1*) those containing 12–18% of antimony and up to 5% of tin; (*2*) a slightly harder bearing alloy containing the same amount of antimony but with 10–12% of tin.

Tin-Lead Alloys. Tin alloys easily with lead to form a group of alloys known as soft solders. (See *Solders and brazing alloys.* See also *Indium*; *Lead alloys.*) Because of their unique properties, the tin-base solders have no serious competitors in the field of low-temperature soldering.

Tin is the important element in soft solders, since it is the constituent that does the adhering. It adheres readily to most metals and alloys, particularly such common metals as iron, steel, and copper. Tin has a low melting point (450°F.) and is sometimes used alone as a solder, as, for example, in soldering galvanized iron. However, mixed with nonadhering lead, not only is the melting point reduced considerably but the alloy is cheaper and in most cases the joint is much stronger. A 50–50 mixture of

tin and lead makes the strongest joints. This is the popular, general purpose, solder alloy.

Bibliography

(1) A.S.T.M., "Symposium on Tin," *Special Tech. Pub.*, No. **141** (1952).
(2) Britton, S. C., *The Corrosion Resistance of Tin and Tin Alloys* (THH), Tin Research Inst., Greenford, Middlesex, England, 1952.
(3) Clark, F. H., Everhart, J. L., Gonser, B. W., Hack, C. H., and Vogelsang, E., "Tin and Tin Alloys" in *Metals Handbook*, Am. Soc. Metals, Cleveland, Ohio, 1949, pp. 1063–76.
(4) Faulkner, C. J., *The Properties of Tin* (ITC), Tin Research Inst., Greenford, Middlesex, England, 1954.
(5) Hallett, R. L., "Tin," in Liddell, *Handbook of Nonferrous Metallurgy*, 2nd ed., McGraw-Hill, N.Y., 1945, Vol. II, ch. 24, pp. 656–79. Fig. 1 courtesy McGraw-Hill Book Co.
(6) International Tin Study Group, *Statistical Bulletin* (May 1954).
(7) Jones, E. H., "Refining of Tin," in *The Refining of Non-Ferrous Metals*, Symposium, The Institute of Mining and Metallurgy, London, 1950, pp. 347–66.
(8) Langer, N. J. (ed.), *Metal Statistics—1954*, 47th ed., American Metal Market, N.Y., 1954, 848 pp.
(9) Lewis, W. R., *Notes on Soldering* (HN), Tin Research Inst., 1951.
(10) Mantell, C. L., *Tin: Its Mining, Production, Technology, and Applications*, 2nd ed., Reinhold, N.Y., 1949.
(11) National Production Authority, *Materials Survey, Tin*, June 1953.
(12) Nekervis, R. J., and Gonser, B. W., "Tin," in Mathewson, *Modern Uses of Nonferrous Metals*, 2nd ed., American Inst. Mining Met. Engrs., N.Y., 1953, pp. 410–31.
(13) Price, J. W., *The Chemical Analysis of Tin-Lead Solders* (TCO), Tin Research Inst., Greenford, Middlesex, England, 1950.
(14) Price, J. W., *Sampling and Analysis of Tin Ingots* (THE), Tin Research Inst., Greenford, Middlesex, England, 1951.

R. J. NEKERVIS AND R. M. MACINTOSH

DETINNING

Detinning, as the term is used in the industry, refers to the processing of tinplate scrap for the recovery of the tin coating and the reclamation of the base steel. The bulk of the scrap thus treated originates in the manufacture of tin cans, although some is derived from miscellaneous fabricating industries using tin plate. A small fraction of a potentially large source in the form of used tin cans is also processed.

The tin plate which is the basic raw material for the can manufacturing industry is sheet steel, commonly about 0.01 in. thick, with a coating of pure tin averaging somewhat less than 1% of the weight of the steel. This percentage of tin is sufficient to make the scrap unsuitable for return to steel furnaces, where the surface coating would alloy with the steel in the melting process and impair the properties of the finished product. It is essential, therefore, that the tin be removed from the steel before the latter has any value as scrap in steelmaking. This fact, together with the value of the tin recoverable, has long stimulated the imagination of inventors, and led to the establishment of a considerable detinning industry prior to 1900 in the U.S. and earlier in Germany. The growth of the industry has roughly paralleled that of can manufacturing, which has been its principal source of raw material.

OLDER PROCESSES

Since the middle of the 19th century hundreds of patents have been issued covering a wide variety of detinning processes and equipment. These have included physical

methods such as volatilizing or melting the tin off the steel, chemical methods using a wide variety of different agents, amalgamation with mercury or alloying with other metals, and several types of electrolytic processes. Many of these never were used, since they were quite impractical from a chemical or cost standpoint. Some were tried briefly, then abandoned. Of the others, three processes have accounted for nearly all commercial detinning: (*1*) alkaline electrolytic process, (*2*) chlorine process, and (*3*) alkali chemical process. The first two are outlined briefly for their historical importance, although they have been generally superseded by the alkali chemical process.

Patents on the use of electrolysis in alkaline solution and on the use of chlorine for detinning date back as far as 1876 and 1854, respectively. It was not until 1882, however, that the growth of commercial electric power facilities favored the establishment of an *electrolytic* detinning industry in Germany. Prominent among early producers was the Goldschmidt Detinning Company. The process consisted essentially of electrolysis in a hot solution of caustic soda, with the tin-plate scrap as anode and steel plates as cathodes. The tin was dissolved from the scrap and deposited on the cathodes in spongy form; it was then scraped off, washed, dried, and smelted to form pig tin. Details of this process have been given by Mantell (2). Considerable tonnages of scrap were detinned by this method, but the necessity for handling the material in relatively small batches made labor costs high.

The *chlorine* process, which began to supplant the electrolytic method on an extensive scale about 1907, was based on the fact that dry chlorine reacts readily with tin at low temperatures to form tin tetrachloride without affecting the iron. The reaction was carried out in large iron cylinders, and the tin tetrachloride was recovered as anhydrous liquid $SnCl_4$, b.p. 114°C., which was either marketed as such or converted to tin oxide. Success of the process depended on completely excluding moisture and maintaining the temperature below about 50°C.; otherwise the iron was attacked with formation of ferric chloride. Mantell (3) has described some of the variations of the process; these deal mainly with the control of pressure, dilution of chlorine with air, and use of chlorine in an anhydrous solvent such as stannic chloride or carbon tetrachloride.

Advantages of chlorine detinning lay chiefly in the lower labor costs inherent in the process and in the handling of large batches, and in the direct recovery of a valuable product in the form of stannic chloride. The latter found its principal market in the dyeing and weighting of silk. This market largely disappeared about 1936, partly as a result of the rapid growth of the rayon industry, and this compelled the detinning industry to shift emphasis to other products. Some stannic chloride was converted to oxide, but the industry soon changed over to the alkali chemical process which forms the basis for most present American detinning practice.

ALKALI CHEMICAL PROCESS

In the alkali chemical process the scrap is treated with a hot solution of caustic soda in the presence of an oxidizing agent, commonly sodium nitrate or nitrite, whereby the tin is dissolved as sodium stannate and the steel remains unaffected. The steel is rinsed and pressed into bales for shipping.

The tin may be recovered from the stannate solution (*1*) as sodium stannate crystals, $Na_2SnO_3.3H_2O$, (*2*) as metal by electrolysis, or (*3*) as tin oxide by neutralization of the solution. Neutralization may be carried out either with sulfuric acid (1) or with carbon dioxide, as indicated in the following equations:

$$Na_2SnO_3 + H_2SO_4 \longrightarrow SnO_2 + Na_2SO_4 + H_2O$$

$$Na_2SnO_3 + CO_2 \longrightarrow SnO_2 + Na_2CO_3$$

The choice of neutralizing agent depends on circumstances. Availability of cheap sulfuric acid may favor the first, whereas the second process offers an advantage in

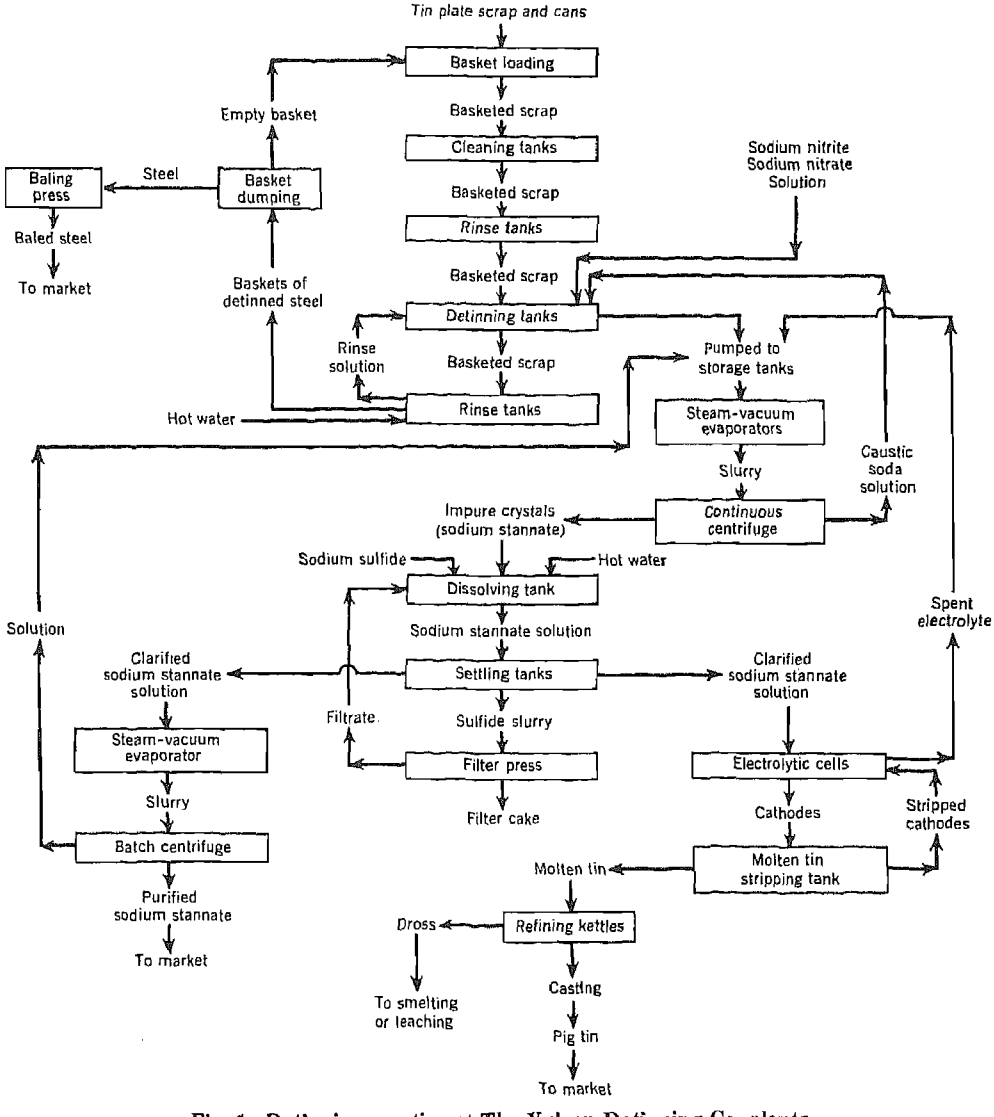


Fig. 1. Detinning practice at The Vulcan Detinning Co. plants.

permitting recovery of sodium hydroxide by recausticizing the sodium carbonate solution with lime. In either case, the tin oxide recovered is usually smelted to obtain pig tin.

Electrolysis of the stannate solution to yield metallic tin directly is standard practice in several plants. This has certain advantages in processing cost, as well as in giving directly a metal of high purity. As a matter of fact, most of the tin produced

as a result of detinning operations today is of superior quality, generally assaying better than 99.95% pure. This is understandable in view of the nature of the raw material and the process steps involved.

Outstanding advantages of the alkali chemical process over the old electrolytic detinning process are the handling of scrap in large batches of several tons instead of in small units of from fifty to a few hundred pounds and the much greater purity of the tin recovered. The metal obtained by the old process was generally heavily contaminated with lead, limiting its use to the production of solder and other alloys.

Illustrative of present practice is the operation of the plant of The Vulcan Detinning Company at Neville Island, Pennsylvania. A caustic soda solution leaching process is used, with sodium nitrate and sodium nitrite as oxidizing agents. Tin is recovered as metal by electrolysis. Operations at this plant are shown in the flow diagram in Fig. 1.

Tin-plate scrap, consisting of punch press skeleton sheets, punchings, trimmings, shredded cans, and defective sheets, is loaded directly into detinning baskets. These consist of large perforated steel plate cylinders, supported in a horizontal position on end trunnions attached to a structural steel frame. A removable section or lid which extends the full length of the basket provides the opening for loading and unloading the scrap. A drive on each of the 24 scrap-treating tanks is used to revolve the baskets; this creates a movement within the mass of scrap and insures access of the solutions to all surfaces.

All tanks and equipment exposed to the detinning solutions are of steel construction. Steam coils in the detinning and cleaning tanks supply the heat required to maintain temperature of the solutions at 205–210°F.

Cleaning solutions contain 10 g. per liter of sodium hydroxide and are used to remove the organic enamels which may be used as coatings over the tin. The organic coatings dissolve in the solutions, which periodically are discarded and replaced with fresh solutions. After cleaning, scrap is rinsed with hot water before placing in the detinning tanks.

Detinning solutions are hot caustic soda solutions containing sodium nitrate and sodium nitrite. The tin is leached from the surface of the steel; reactions are as follows:

$$2\,Sn + 3\,NaOH + NaNO_3 \longrightarrow 2\,Na_2SnO_3 + NH_3$$

$$3\,Sn + 3\,NaOH + 3\,NaNO_2 \longrightarrow 3\,Na_2SnO_3 + N_2 + NH_3$$

The detinning solutions are made up to contain 80 to 90 g. per liter of sodium hydroxide, and additions of a concentrated solution of sodium nitrate and sodium nitrite are made as required. Operations in each detinning tank are on a batch basis, and when a concentration of about 50 g. per liter of tin is reached, the solutions are pumped to storage tanks. About three hours is required to detin each basket of scrap. Four rinse tanks provide a countercurrent washing system for the baskets of detinned scrap. Hot water, after flowing through the rinse system, is used to maintain the proper level in the detinning tanks and in the making up of starting solutions.

Detinned scrap is compressed into bales weighing about 600 lb. with a hydraulically operated baling press. The baled steel contains a maximum of 0.03% surface tin and is marketed as heavy melting steel scrap.

Detinning solutions and spent electrolyte are sent to the evaporators, where most of the tin is crystallized out as hydrated sodium stannate ($Na_2SnO_3.3H_2O$). The high-

gravity solution from the evaporators is returned to the detinning tanks after the sodium stannate has been separated in a continuous solid bowl centrifuge. The impure sodium stannate is dissolved in hot water and sodium sulfide is added to precipitate lead and zinc; the reactions are as follows:

$$Na_2PbO_2 + Na_2S + 2\,H_2O \longrightarrow PbS + 4\,NaOH$$

$$Na_2ZnO_2 + Na_2S + 2\,H_2O \longrightarrow ZnS + 4\,NaOH$$

Accumulations of sulfide precipitates which settle out of the sodium stannate solution are slurried in water and filtered on a plate and frame filter press.

The clarified sodium stannate solution contains from 110 to 120 g. per liter of tin and is sent to the electrolytic cells or is evaporated to produce a purified sodium stannate, which is marketed chiefly for use in the tin electroplating industry.

The electrolytic cell system contains 112 cells in seven rows of 16 cells each; the electrolyte enters the first row and flows through the seven rows before leaving as spent electrolyte. The electrolyte in each cascaded row of cells is circulated through a heat exchanger to maintain a temperature of 190–200°F. Tin is deposited at the cathode in a dense, smooth form and oxygen is evolved at the anode. Steel electrodes are used. Cells are rectangular steel tanks, each containing 12 cathodes and 13 anodes.

Cells are usually operated at a current density of 8 to 12 amp. per square foot, with an average current efficiency of 75% (546 amp.-hr. per pound of tin). All cells are connected in series and operate at about 2.2 v. each. Cathodes are pulled for stripping when the tin deposit has built up to a thickness of approximately $\frac{3}{16}$ in.

The tin is melted from the cathode plates in a tank of molten tin, stripped tin overflowing into refining kettles. Small amounts of iron and zinc are removed in a kettle treatment. The small amount of dross produced contains 85–90% tin and may be smelted to recover the tin.

Refined electrolytic tin is cast into 100 lb. pigs. The tin produced averages about 99.97% pure, with small amounts of antimony, iron, and lead as principal impurities.

ECONOMIC ASPECTS

The largest single use of tin is in tin plate, of which the major portion goes into the making of cans. It is estimated that approximately 10–15% of the tin plate thus used is left as scrap. This, together with scrap from miscellaneous fabricating operations, furnishes a large tonnage of relatively uniform raw material for the detinning industry. In addition, used tin cans comprise a source which may be exploited as circumstances dictate; during World War II they were processed in large quantities to yield considerable tonnages of steel and tin. Production figures for the U.S. detinning industry for the years 1933–52, as given by the Bureau of Mines (4), are listed in Table I. Prior to 1936 the bulk of the tin was recovered in the form of tin compounds, principally stannic chloride. With the sharp decline in the use of this compound in connection with the weighting of silk there was an immediate reversal of the ratio of metal to compounds as the final form of the recovered tin, and in recent years approximately 85–90% of the tin has been marketed as metal.

Although the tonnage of scrap treated annually has approximately tripled since 1933, the tonnage of tin recovered has decreased somewhat since 1942. This can be attributed to the introduction of electrolytic tin plate in the early part of the war and the subsequent steady supplanting of hot-dipped tin plate by the electrolytic

TABLE I. Detinning Operations in the United States, 1933–52.

Year	Scrap treated (long tons)			Tin recovered (short tons)			Lb. tin recovered per long ton scrap	
	New scrap	Cans	Total	As metal	As compounds	Total	From new scrap	From cans
1933	155,844	—	155,844	938	2,008	2,946	37.8	
1938	209,474	3,059	212,533	2,534	1,389	3,923	37.1	
1939	248,676	6,429	255,105	4,089	680	4,769	37.7	
1940	268,269	4,963	273,232	4,147	697	4,844	35.7	
1943	206,336	175,870	382,206	4,327	250	4,577	25.1	22.6
1945	257,545	114,311	371,856	3,527	454	3,981	22.6	18.7
1950	469,417	16,818	486,235	3,697	644	4,341	18.0	14.3
1952	439,321	25,890	465,211	2,952	350	3,302	14.2	14.3

product. Whereas the former carried an average of well over 1% tin, electrolytic coatings have been largely standardized at ¼, ½ and ¾ lb. of tin per base box, equivalent roughly to 0.25, 0.50, and 0.75% tin on the steel. This trend is well illustrated in the figures for pounds of tin recovered per ton of scrap.

The United States, since it has virtually no domestic sources of tin ore and is the world's largest consumer of tin, is dependent on imports and on secondary recovery. Since the largest single use of tin is in the manufacture of tin cans, this presents the greatest potential source for secondary recovery. Detinning plants already do an efficient job in processing the scrap incident to can manufacture, but the cans themselves, except for a very small fraction sent to detinners, generally end up on the dump with a total loss of the associated tin. Under sufficient incentive, as was demonstrated during World War II, much of this could be salvaged. Obstacles to large-scale detinning of used cans are economic rather than technical and depend chiefly on the cost of collecting the cans.

Bibliography

(1) Krombholz, A. J., *Iron Steel Engr.*, **30**, No. 3, 98–105 (1953).
(2) Mantell, C. L., *Tin*, 2nd ed., Reinhold, N.Y., 1949, pp. 519–523.
(3) Mantell, C. L., *Tin*, 2nd ed., Reinhold, N.Y., 1949, pp. 526–529.
(4) *U.S. Bur. Mines, Minerals Yearbook*, yearly editions.

L. E. SWANSON AND R. H. TAYLOR

TIN BRASS; TIN BRONZE. See *Copper alloys (wrought)*, Vol. **4**, p. 454; *Copper alloys (cast)*, Vol. **4**, p. 461.

TIN COATING, TIN PLATING. See *Electroplating*, Vol. **5**, p. 639; *Metallic coatings*, Vol. **8**, p. 905.

TIN COMPOUNDS

Tin, with an atomic structure of two *s* and two *p* electrons, exhibits valence numbers of +2 and +4. It forms stannous, Sn^{2+}, and stannic, Sn^{4+}, compounds, as well as complex salts of the stannite, M_2SnX_4, and stannate, M_2SnX_6, type. Tin compounds have been known from very early times. The Copts of Egypt are believed to have used a basic citrate of tin in the preparation of dyes, and the alchemists prepared stannic chloride. Industrial tin compounds have wide use in industry, in the fields of textiles, ceramics, and metal coatings. The U.S. peacetime consumption of tin compounds, based on Dept. of Commerce figures, is about 1000 tons per year as shown in Table I.

TABLE I. Consumption of Tin Chemicals in the United States.

Tin content, gross tons	1940	1942	1944	1946	1948	1950	1952
Tin chemicals[a]	382	246	293	601[b]	226	817	687
Tin oxide	1157	131	—	—	274	890	396

[a] Other than tin oxide.
[b] Includes miscellaneous.

The bulk of the tin chemicals consumed in the U.S. is domestically produced, a large portion from tin alloys scrap, and as a direct by-product of detinning operations (see *Tin and tin alloys* (*detinning*)), but some tin salts are imported. There is an import duty of 12½% ad valorem on all chemicals in which tin constitutes the chief value (1953). Prices for the tonnage tin chemicals fluctuate with the price of the metal.

Although a great many inorganic tin compounds are known and described in the literature, only about fifty are of more than passing interest, and no more than ten are produced industrially on a substantial scale. Most of these are stannous compounds, the dichloride (both anhydrous and hydrated), sulfate, oxide, fluoborate, oxalate, and the tin soaps; stannic compounds available commercially are the tetrachloride, the dioxide, and the sodium and potassium stannates and some heavy-metal stannates. The years of World War II brought about a severe reduction in the consumption of tin compounds, and in some fields salts of other less critical metals have been used instead of tin chemicals. However, new uses for tin chemicals are constantly being found and ground lost in some fields is being made up in others. See also "Metallic soaps having nondrier uses" under *Driers and metallic soaps*, Vol. **5**, p. 206; *Organometallic compounds*, Vol. **9**, p. 633.

Bivalent tin salts are most conveniently obtained from stannous oxide, SnO, or the hydroxide, $Sn(OH)_2$, both of which react very readily. Stannic oxide, SnO_2, or preferably hydrated stannic oxide, readily yields a water-soluble alkali metal stannate. Water-insoluble stannates are generally prepared by double decomposition reactions. In many cases, such as the chlorides, the metal itself is used as the starting material. Cassiterite is seldom used as a raw material because of its refractory nature, which makes it yield only to alkaline fusions.

Stannane. See "Tin hydride."

Stannates. See under "Tin oxides and hydrated oxides."

Thiostannates. See under "Tin sulfides."

Tin Acetates.

Stannous acetate (14), $Sn(C_2H_3O_2)_2$, formula weight 236.79, is a colorless crystalline salt which finds use in the textile industry to promote exhaustion of dyes. A solution of it may be prepared by double decomposition of lead acetate and stannous chloride, or by dissolving stannous oxide in glacial acetic acid. This solution is the article of commerce. The dry salt can be prepared by precipitation with alcohol.

Stannic acetate (18), $Sn(C_2H_3O_2)_4$, formula weight 354.9, can be prepared by reaction of thallous acetate with tin tetraiodide in acetic anhydride:

$$4\,Tl(C_2H_3O_2) + SnI_4 \longrightarrow Sn(C_2H_3O_2)_4 + 4\,TlI$$

It is a white crystalline salt, m.p. 253°C. It hydrolyzes very readily in moist air.

Tin Bromides. See under "Tin halides."

Tin Chlorides. See under "Tin halides."

Tin Chromate.

Stannic chromate is a yellow-brown powder obtained by treating solutions of stannic chloride with potassium dichromate.

Chrome-tin pink is a ceramic pigment (see Vol. 4, p. 286).

Tin Fluoborate.

Stannous fluoborate (6), $Sn(BF_4)_2$ formula weight 292.34, forms the basis of a commercially important tin plating bath. It is made by dissolving stannous oxide in fluoboric acid. It is commercially available only in the form of a 47% solution.

Tin Fluoride. See "Tin halides."

Tin Formate.

Stannous formate (25), $Sn(CHO_2)_2$, formula weight 208.74, forms white anhydrous crystals which decompose in air above 100°C. It is obtained by treating stannous oxide with formic acid below 60°C. Its use in the hydrogenation of fuels in the liquid phase has been patented (25).

Tin Halides.

Stannous chloride (4,30,34), $SnCl_2$, formula weight 189.61, m.p. 246.7°C., is soluble in water, alcohol, glacial acetic acid, and many organic solvents. It forms a hydrate, $SnCl_2.H_2O$. The hydrate, which melts at 37–38°C. with decomposition, is soluble in water, alcohol, ethyl acetate, and glacial acetic acid. On standing it undergoes internal decomposition to form a basic salt by loss of hydrogen chloride.

Stannous chloride solutions are strongly reducing. The more dilute aqueous solutions tend to hydrolyze, but can be stabilized by the addition of small amounts (0.25–1%) of hydrochloric acid. Addition of alkalies precipitates a hydrated oxide, which reacts with excess alkali to form soluble stannites.

The anhydrous salt may be made by direct reaction of chlorine and molten tin. The hydrated salt is obtained by treating flaked tin with hydrochloric acid, followed by evaporation and crystallization, or by cathodically reducing a solution of stannic chloride.

Uses of stannous chloride include electrotinning of steel strip in the so-called

halogen process, immersion tinning processes, tin coating of paper, antisludge agent for lubricating oils, stabilization of perfumes in soaps, catalyst in organic reactions, activator in electrodeposition of plastics and in silvering of mirrors, and ingredient in drilling mud conditioners.

Complex salts of stannous chloride are known as the **chlorostannites** (chlorostannates(II)). Many of them can be prepared by evaporation of solutions of the component salts. The anions $SnCl_3^-$, $SnCl_4^{2-}$, and $SnCl_6^{4-}$ are known, and salts such as ammonium trichlorostannate(II), $NH_4SnCl_3.H_2O$, ammonium tetrachlorostannate(II), $(NH_4)_2SnCl_4.2H_2O$, and ammonium pentachlorostannate(II), $(NH_4)_3SnCl_5.3H_2O$, have been reported. They are described as stable in air, but some may lose their water of hydration.

Stannic chloride (tin tetrachloride) (2,32,35,36,38,40,43), $SnCl_4$ (the *"spiritus argenti vivi sublimati"* of Libavius, first described in 1605), formula weight 260.53, m.p. −30.2°C., b.p. 114°C., sp.gr. 2.23, is a colorless fuming liquid. It is soluble in water with evolution of heat. It is a nonconductor. It forms a number of solid or semisolid hydrates which are sold commercially. Tin tetrachloride is miscible with alcohol, carbon tetrachloride, benzene, toluene, kerosine, and other organic solvents. It can be prepared in various ways, but the simplest method which is used commercially on a large scale is the direct chlorination of tin, either as molten metal or suspended as finely divided tin under tin tetrachloride. Stannous chloride may also be formed, but stannic chloride can be separated from it easily since it is a gas at the operating temperature. The bulk of the tin tetrachloride consumed in the U.S. was at one time supplied by the chlorination of tin plate (see *Tin and tin alloys (detinning)*.

Tin tetrachloride may safely be handled in plain steel equipment in the absence of moisture. It is shipped in steel drums.

The use of tin tetrachloride as a mordant in silk dyeing is quite old. The weighting of silk by means of tin tetrachloride is, however, a development of the 50 years before about 1935. From then on this use, which at one time accounted for most of the tin tetrachloride consumption of the world, decreased rapidly. Today, tin tetrachloride still finds many diverse uses, of which the largest one is probably in the preparation of organotin compounds.

Tin tetrachloride forms a series of **chlorostannates** (hexachlorostannates(IV)), M_2SnCl_6. The hexahydrate of H_2SnCl_6 has been reported by several authors. It is stated that it loses hydrogen chloride and water in air to form $SnCl_4.5H_2O$. The following chlorostannates have commercial importance. *Ammonium chlorostannate*, $(NH_4)_2SnCl_6$, formula weight 367.53, is a white crystalline salt readily soluble in cold and hot water. The compound used to be known as "pink salts," and under this name was widely used in the textile industry before pure tin tetrachloride and pure tin tetrachloride pentahydrate became commercially available. *Sodium chlorostannate*, $Na_2SnCl_6.5H_2O$, formula weight 467.43, is a white crystalline salt readily soluble in cold and hot water. It has been used for the same purpose as the ammonium salt.

Stannous bromide, $SnBr_2$, formula weight 278.5, is a light yellow crystalline salt, m.p. 232°C., b.p. 618°C., which is hydrolyzed by water and is also sensitive to light. It is prepared by dissolving tin in concentrated hydrobromic acid. From this solution, a product, $SnBr_2.2HBr.8H_2O$, can be isolated, which is decomposed by heat to yield stannous bromide. Stannous bromide combines with metal bromides to form a series of *bromostannites* which are analogous to the chlorostannites.

Stannic bromide, $SnBr_4$, formula weight 438.4, is a crystalline, slightly hygroscopic substance prepared with ease from tin and bromine; m.p. 33°C., b.p. 201°C. It is very stable thermally and can be purified by distillation but it is decomposed by water. Because of its low melting point and high specific gravity (3.31), it finds use in the laboratory for the metallurgical separation of minerals. Stannic bromide forms a series of *bromostannates*, M_2SnBr_6.

Stannous iodide, SnI_2, formula weight 372.5, is a slightly water-soluble substance which forms deep red crystals melting at 320°C. and boiling at 720°C. It is prepared from tin and concentrated hydroiodic acid. A number of *iodostannites* are known, most of which are decomposed by water.

Stannic iodide, SnI_4, formula weight 626.4, m.p. 143.5°C., b.p. 340°C., forms yellow to reddish crystals which are decomposed by water. Of the complex *iodostannates*, M_2SnI_6, only the salts of rubidium and cesium have been reported. The salts of ammonium, sodium, and potassium could not be prepared (1).

Stannous fluoride, SnF_2, molecular weight 156.70, forms opaque, lustrous crystals which are quite soluble in cold water. It is readily prepared from stannous oxide and hydrofluoric acid. It has shown promise in preventing decalcification of teeth (15).

Stannic fluoride, SnF_4, formula weight 194.70, is chiefly a laboratory curiosity. Its solution in water is more stable than that of the chloride. Stannic fluoride forms the basis of a series of *fluostannates* containing the complex ion SnF_6^{2-}, none of which have commercial importance.

Tin Hydride.

Tin tetrahydride (stannane) (14), SnH_4, formula weight 122.73, is the only known hydride of tin. It is a gas at room temperature and undergoes slow decomposition, which becomes very rapid at 145–150°C. It can be prepared by treating stannic chloride with lithium aluminum hydride, $LiAlH_4$, in diethyl ether at −30°C. This compound can also be prepared in dilute aqueous hydrochloric acid (0.6*N*) by the action of sodium borohydride, $NaBH_4$, on stannous chloride according to the equation:

$$4\,Sn^{2+} + 3\,BH_4^- + 6\,H_2O \longrightarrow 4\,SnH_4 + 3\,HBO_2 + 5\,H^+$$

The sodium borohydride hydrolyzes, and considerable amounts of borates, principally metaborates, are produced. By varying the concentration of the tin compounds, conversions to stannane up to 100 per cent can be obtained (16). This method is adaptable to the quantitative determination of tin in small quantities. Tin hydride has been used to gas-plate tin on metal and ceramic surfaces.

Tin Nitrates.

The existence of either stannous nitrate or stannic nitrate in the solid state must be questioned, although both compounds were claimed to have been made before 1900. Solutions of such nitrates can, however, be made. Those containing stannous tin must be prepared cold, and they are quite unstable. All solutions containing tin and nitric acid decompose on aging and upon heating and dilution.

Tin Oxalate (11,14).

Stannous oxalate, $Sn(C_2O_4)_2$, formula weight 206.72, is a white, heavy powder, sparingly soluble in either hot or cold water, but readily soluble in strong hot hydro-

chloric acid. It is prepared in almost quantitative yield by precipitating a stannous chloride solution with oxalic acid. It has excellent stability on storage. Stannous oxalate was used during World War II in Germany as a coal hydrogenation catalyst, and was also used for this purpose in the U.S. at the Bureau of Mines' coal hydrogenation demonstration plant at Louisiana, Mo. Stannous oxalate is also used for sensitizing blueprint papers.

Tin Oxides and Hydrated Oxides; Stannites; Stannates.

Stannous oxide, SnO, formula weight 134.70, is a very dark, usually blue-black, crystalline substance of high metallic luster. The shade may vary from brown and red to dark green and violet, depending on the method of preparation. It is obtained by first precipitating a solution of stannous chloride with alkali to yield stannous hydroxide and then converting the latter to the oxide at temperatures near the boiling point of water and at a controlled pH. Stannous oxide is thermally stable up to 385°C. when it decomposes into tin and stannic oxide:

$$2\,SnO \xrightarrow{heat} Sn + SnO_2$$

When heated in air it readily forms stannic oxide. Stannous oxide dissolves in acids to give stannous salts. It does not, in contrast to stannous hydroxide, dissolve in potassium or sodium hydroxide.

The chief use of stannous oxide is as an intermediate in the manufacture of other tin compounds. It is also used in the glass industry in the manufacture of gold-tin and copper-tin ruby glass. In the past it has been used in medicine as a remedy for boils; this was based on the observation that workers in tin mines are free from boils.

Stannous hydroxide, $Sn(OH)_2$, can be obtained as a white precipitate from solutions of stannous salts by means of alkalies. It is probably a hydrated oxide rather than a true hydroxide. It readily oxidizes in air to hydrated stannic oxide. It dissolves in potassium or sodium hydroxide to form solutions of potassium or sodium **stannites,** probably containing the anion SnO_3^{2-}. Stannites are only known in the form of their solutions, which readily decompose into alkali metal stannates and tin. The sodium stannite solutions are used industrially in immersion tinning (42).

Stannic oxide (tin oxide) (9,24,26,27,28,29,39,47), SnO_2, formula weight 150.70, forms white tetragonal crystals. Its melting point is well above 1600°C., although many handbooks list it as 1127°C. It is prepared industrially by blowing heated air over molten tin, by atomizing tin by means of high-pressure steam and burning the finely divided metal, or by the calcination of the hydrated oxide (see below). Stannic oxide can also be prepared by treating tin tetrachloride with steam at high temperatures according to the equation:

$$SnCl_4 + 2\,H_2O \xrightarrow{heat} SnO_2 + 4\,HCl$$

Stannic oxide is an ingredient in certain ceramic colors such as chrome-tin pink (see p. 158) and vanadium-tin yellow. Substantial quantities of this oxide are consumed as putty powder (see Vol. **1,** p. 57) for polishing marble and granite.

Hydrated stannic oxide (often referred to as "stannic acid") of variable water content can be obtained by the hydrolysis of stannates. X-ray studies have failed to show characteristic patterns for stannic acids prepared by radically different methods, and all of these acids give cassiterite, SnO_2, on calcination. They must be regarded

as amorphous stannic oxides that are hydrated to a variable extent. They do, nevertheless, exhibit distinctly different properties for considerable lengths of time, depending on their method of preparation, which in turn governs the degree of polymerization. The more highly hydrated and more soluble form is known as α-stannic acid, and the less hydrated and less soluble form as β-stannic acid. The terms orthostannic acid and metastannic acid have also been used for the α- and β-forms, respectively. α-Stannic acid is irreversibly transformed into β-stannic acid by heating, drying, or prolonged standing. α-Stannic acid is obtained by the decomposition of solutions of alkali metal stannates with acids or by the decomposition of a solution of stannic chloride with alkali or excess water. When these operations are carried out at room temperature the precipitate has the stoichiometric composition $Sn(OH)_4$. Drying at 100°C. causes the loss of one molecule of water and conversion to β-stannic acid, having the stoichiometric composition H_2SnO_3.

Freshly prepared α-stannic acid is readily soluble in caustic alkalies, forming the stannates, and in hydrochloric acid, forming stable solutions in which at least part of the tin is present as Sn^{4+} ion. β-Stannic acid is soluble in dilute hydrochloric acid, but the addition of more acid gives a precipitate, which in boiling water hydrolyzes to $H_2Sn_5O_{11}.4H_2O$. β-Stannic acid can be peptized by potassium hydroxide to give colloidal solutions, but the reports of definite salts such as $K_2Sn_5O_{11}.4H_2O$ and $Na_2Sn_5O_{11}.4H_2O$ must be doubted. A product possibly identical with β-stannic acid is obtained as a white powder by the oxidation of tin with nitric acid.

The metal **stannates** (10,12,21,23,44,46) include a large number of compounds but at present only the alkali metal stannates are of established commercial importance and manufactured on a large scale. The hydroxostannates have the general formula $M_2[Sn(OH)_6]$. Hydrates, $M_2[Sn(OH)_6].H_2O$, are known; they lose one molecule of water readily at 100°C., or *in vacuo*. Potassium stannate is isomorphous with potassium plumbate, $K_2[Pb(OH)_6]$, and potassium platinate, $K_2[Pt(OH)_6]$.

Sodium stannate, $Na_2Sn(OH)_6$, formula weight 266.74, consists of white, colorless crystals, which absorb carbon dioxide from the air to form sodium carbonate and hydrated stannic oxide. It is readily soluble in cold water (61.5 g./100 ml. H_2O at 15°C.), but its solubility decreases with increasing temperature. Solutions of sodium stannate decompose under pressure and at temperatures above 150°C. to yield stannic oxide. The domestically produced commercial grade of sodium stannate is a product of the alkaline detinning process. It may also be made from cassiterite by fusing with sodium carbonate or hydroxide.

Both sodium and potassium stannate find wide use as constituents of alkaline electrotin plating baths. They are also used to tinplate aluminum alloy pistons by contact (voltaic displacement).

Potassium stannate, $K_2Sn(OH)_6$, formula weight 298.94, forms colorless crystals of high water solubility (110.5 g./100 ml. H_2O at 15°C.). It readily absorbs carbon dioxide from the air. Like sodium stannate, it is a product of the alkaline detinning process, but it may also be made by alkaline fusion of tin ore and subsequent leaching and evaporation.

Other Stannates (7,50). Some alkaline earth and heavy metal stannates have recently acquired importance in the compounding of ceramic and dielectric bodies. They are insoluble compounds prepared by precipitation of the stannate by the action of a soluble salt of the metal on a solution of a soluble alkali metal stannate,

or by calcination of proper mixtures of the respective oxides. A listing by a manufacturer of tin chemicals includes the following:

Barium stannate	$BaSnO_3.3H_2O$	Nickel stannate	$NiSnO_3.2H_2O$
Calcium stannate	$CaSnO_3.3H_2O$	Copper stannate	$CuSnO_3.3H_2O$
Magnesium stannate	$MgSnO_3.3H_2O$	Cadmium stannate	$CdSnO_3$
Strontium stannate	$SrSnO_3.3H_2O$	Cobalt stannate	$CoSnO_3.2H_2O$
Bismuth stannate	$Bi_2(SnO_3)_3.5H_2O$	Ferrous stannate	$FeSnO_3.3H_2O$
Lead stannate	$PbSnO_3.2H_2O$	Ferric stannate	$Fe_2(SnO_3)_3.3H_2O$
Zinc stannate	$ZnSnO_3.4H_2O$		

Tin Perchlorate.

Stannous perchlorate, $Sn(ClO_4)_2.xH_2O$, formula weight (anhydrous salt) 317.6, forms yellowish deliquescent crystals. It is very stable at room temperature, but decomposes on heating above 100°C. Stannous perchlorate is made by dissolving stannous oxide in perchloric acid. It forms the basis of a tin plating solution.

Tin Phosphates (5,13,48).

References to the following tin phosphates can be found in the literature: stannous orthophosphates, $Sn_3(PO_4)_2$, $SnHPO_4$, $Sn(H_2PO_4)_2$; stannous pyrophosphate, $Sn_2P_2O_7$; stannous metaphosphate, $Sn(PO_3)_2$; stannic phosphate, $Sn_2P_2O_9.10H_2O$.

Of these salts the only one to have commercial significance is **stannous pyrophosphate,** $Sn_2P_2O_7$, formula weight 411.5, an amorphous white powder, soluble in sodium pyrophosphate and hydrochloric acid. It is prepared from stannous chloride and sodium pyrophosphate. It is used as a constituent of one of several alkaline tin plating baths for co-depositing a copper-tin alloy of controlled composition.

Tin Proteinate.

Tin proteinate (tin albuminate) is manufactured from a salt of bivalent tin and gelatin. It is a pale yellow to light buff powder possessing a slight characteristic odor. The product contains 9% tin, and is used in the form of an ointment for carbuncles and other skin eruptions.

Tin Sulfates (3,17,19,23,45).

Stannous sulfate, $SnSO_4$, formula weight 214.77, is a heavy white crystalline powder, thermally stable up to about 360°C. It is soluble in water to the extent of 330 g. per liter of solution at 25°C., as calculated from data published by Denham and King (8). A much lower value commonly found in many handbooks is in error. It has a lower solubility at higher temperatures. The solubility of stannous sulfate in water is strongly depressed by the presence of free sulfuric acid or sulfate ions.

In one published method of manufacture, granulated tin is subjected to the action of an excess of dilute sulfuric acid (sp.gr. 1.53) for a period of days at a temperature in excess of 100°C. until all reaction has ceased (17). The stannous sulfate which has formed is extracted with water and the aqueous solution is evaporated *in vacuo*. Excess acid is removed by washing with alcohol.

Stannous sulfate is the principal ingredient of the acid tin plating bath for electroplating steel strip (see *Electroplating*). Because of balanced anode and cathode efficiencies, this bath requires little addition of sulfate.

The main outlet for stannous sulfate is for immersion-plating steel wire with tin or copper-tin alloy coatings before drawing. This operation is known as liquor finishing and is applied to both low- and high-carbon steel wire. The primary purpose of these coatings is to ease the passage of the wire through the die.

Stannic sulfate, $Sn(SO_4)_2.2H_2O$, is said to have been prepared but the evidence presented is open to question. Aqueous sulfuric acid solutions containing stannic tin hydrolyze rapidly. The existence of stable double sulfates of stannic sulfate with other metal sulfates, such as those of potassium, calcium, silver, and lead, seems to be well substantiated (23).

Tin Sulfides (10,14).

Stannous sulfide, SnS, formula weight 150.77, forms dark gray crystals or a black amorphous powder with melting points at 882°C. and 1200°C., respectively. It can be prepared from the elements by direct reaction.

Stannic sulfide (mosaic gold), SnS_2, formula weight 182.83, forms golden leaflets with a metallic luster and a touch resembling that of talc. It has long been in use as the pigment component of nonmetallic bronzes. There are many recipes for its preparation, and most of them involve high temperature sublimation of the product, usually in the presence of a volatile chloride such as ammonium chloride. It has been stated that these volatile chlorides suppress the dissociation of stannic sulfide into stannous sulfide and sulfur, but this explanation is doubtful.

Stannic sulfide dissolves in alkalies to form *thiostannates*; $Na_2SnS_3.8H_2O$ and $Na_4SnS_4.18H_2O$ have been isolated.

Tin Tartrate.

Stannous tartrate, $SnC_4H_4O_6$, formula weight 266.8, is a heavy, white crystalline powder, insoluble in water, but soluble in dilute hydrochloric acid. It can be prepared from solutions of stannous chloride and potassium tartrate. It finds use in dyeing and printing textiles.

Bibliography

(1) Auger, V., and Karantassis, T., *Compt. rend.*, **180,** 1845 (1925).
(2) Brauer, G., *Handbuch der präparativen anorganischen Chemie*, Enke, Stuttgart, 1952.
(3) Camp, J. M., and Francis, C. B., *The Making, Shaping and Treating of Steel*, 5th ed., Carnegie-Illinois Steel Corp., Pittsburgh, Penna., 1940.
(4) *Chem. Inds.*, **47,** 565 (1940).
(5) *Chem. Inds.*, **57,** 889 (1945).
(6) *Chem. Inds.*, **58,** 277 (1946).
(7) Coffeen, W. W., *J. Am. Ceram. Soc.*, **36,** 207–14 (1953).
(8) Denham, H. G., and King, W. E., *J. Chem. Soc. (London)*, **1935,** 1251.
(9) Fraenkel, W., and Snipischski, K., *Z. anorg. u. allgem. Chem.*, **125,** 235–51 (1923).
(10) Jelley, E. E., *J. Chem. Soc. (London)*, **1933,** 1580–81.
(11) Kastens, M. L., Hirst, L. L., and Chaffee, C. C., *Ind. Eng. Chem.*, **41,** 875, 885 (1949).
(12) Lowenheim, F. A., *Trans. Electrochem. Soc.*, **84,** 195–209 (1943).
(13) Mantell, C. L., *Tin* (A.C.S. Monograph No. 51), 2nd ed., Reinhold, N.Y., 1949.
(14) Moeller, T., *Inorganic Chemistry*, Wiley, N.Y., 1952.
(15) Muhler, J. C., Nebergall, W. H., and Day, H. G., *J. Dental Research*, **33,** 33–49 (1954).
(16) Schaeffer, G. W., and Emelius, M., *J. Am. Chem. Soc.*, **76,** 1203 (1954).
(17) Schering, A. G., *Office Tech. Services Rept.*, **PB-74930,** U.S. Dept. Commerce (1948).
(18) Schmidt, H., Blohm, C., and Jander, G., *Angew. Chem.*, **A59,** 233–37 (1947).

(19) Seidell, A., *Solubilities of Inorganic and Metal Organic Compounds*, 3rd ed., Van Nostrand, N.Y., 1940.
(20) Sidgwick, N. V., *The Chemical Elements and Their Compounds*, Vol. I, Oxford University Press, London, 1950.
(21) Sternfels, M., and Lowenheim, F. A., *Trans. Electrochem. Soc.*, 82, 77 (1942).
(22) "Tin and the Paley Report," extract from *Resources for Freedom*, a report to the President by the President's Materials Policy Commission, Govt. Printing Office, June, 1952.
(23) Weinland, R. F., and Kühl, H. , *Z. anorg. Chem.*, 54, 244 (1907).
(24) Brit. Pat. 327,142 (Mar. 27, 1930), to Deutsche Gold und Silber Scheideanstalt.
(25) Brit. Pat. 363,445 (Oct. 11, 1930), P. Askey, R. Holroyd, C. Cockram, and Imperial Chemical Industries, Ltd.
(26) U.S. Pat. 880,873 (March 3, 1908), H. Foersterling (to Roessler and Hasslacher Chemical Co.).
(27) U.S. Pat. 1,028,595 (June 4, 1912), V. Olszewski.
(28) U.S. Pat. 1,362,237 (Dec. 14, 1920), D. deRos.
(29) U.S. Pat. 1,372,407 (Mar. 22, 1921), D. deRos.
(30) U.S. Pat. 1,597,653 (Aug. 24, 1926), W. T. Little.
(31) U.S. Pat. 1,708,392 (April 9, 1929), H. McIlhenney (to Vulcan Detinning Co.).
(32) U.S. Pat. 1,777,132 (Sept. 30, 1930), W. S. Smith.
(33) U.S. Pat. 1,787,078 (Dec. 30, 1930), W. T. Little.
(34) U.S. Pat. 1,825,212 (Sept. 29, 1931), W. S. Smith.
(35) U.S. Pat. 1,826,800 (Oct. 13, 1931), W. Lienhardt.
(36) U.S. Pat. 1,897,360 (Feb. 14, 1933), W. Buttfield (to Vulcan Detinning Co.).
(37) U.S. Pat. 1,919,000 (July 18, 1933), C. Wernlund and F. Oplinger (to Du Pont).
(38) U.S. Pat. 1,937,419 (Nov. 28, 1933), J. Wolf and G. Favre.
(39) U.S. Pat. 1,968,933 (Aug. 7, 1934), E. Feldmann.
(40) U.S. Pat. 2,047,545 (July 14, 1936), W. Buttfield (to Vulcan Detinning Co.).
(41) U.S. Pat. 2,145,433 (Jan. 31, 1939), H. W. Richter.
(42) U.S. Patent 2,159,510 (May 23, 1939), A. E. Pavlish and J. D. Sullivan (to Battelle Memorial Inst.).
(43) U.S. Pat. 2,273,799 (Feb. 17, 1942), M. Jones and G. Heise (to National Carbon Co.).
(44) U.S. Pat. 2,436,974 (March 2, 1948), H. W. Richter (to Metal & Thermit Corp.).
(45) U.S. Pat. 2,543,365 (Feb. 27, 1951), A. W. Harris (to American Steel and Wire Co.).
(46) U.S. Pat. 2,562,577 (July 31, 1951), H. W. Richter (to Metal & Thermit Corp.).
(47) U.S. Pat. 2,621,109 (Dec. 9, 1952), H. W. Richter (to Metal & Thermit Corp.).
(48) U.S. Pat. 2,658,032 (Nov. 3, 1953), C. Faust and W. Hespenheide (to the City Auto Stamping Co.).
(49) U.S. Pat. 2,658,833 (Nov. 10, 1953), W. W. Coffeen and H. W. Richter (to Metal & Thermit Corp.).

HARTMUT RICHTER

TINCTURES. See *Pharmaceuticals*, Vol. **10,** p. 230; and such articles as *Antiseptics*, Vol. **2,** p. 82; *Iodine preparations*; for tincture of green soap, see *Shampoos*, Vol. **12,** p. 223.

TIN-NICKEL BRASS. See *Copper alloys (cast)*, Vol. **4,** p. 461.

TINTS, HAIR DYES AND BLEACHES

Hair colorings	p. 166	Dye removers	p. 186
Temporary	166	Testing of products	187
Permanent	169	Bibliography	188
Bleaching agents	184		

See also *Cosmetics*; *Shampoos and other hair preparations.*

Dissatisfaction with the color of one's hair has led, since earliest times, to the application of various types of natural and man-made substances in attempts to change it. From the earliest Egyptians, through many successors in their cultural heritage—Greeks, Hebrews, Assyrians, Persians—and through the contemporary cultural successors of the ancient Chinese and Hindus, the use of hair colorings is mentioned in historical records of social life and customs (8,16,27,29,32,34,56).

Following the traditional use of botanical simples, vegetal mixtures, and metallic salts, there was little change in coloring products and processes until the last third of the 19th century. The discovery that some of the new synthetic organic compounds were suitable dyes for animal fibers gave impetus to the development of new-type hair colorings, but it was not until the second quarter of the 20th century that they were successfully established in public acceptance.

Statistics on the use of hair colorings and bleaches are unsatisfactory and incomplete. Since 1952, *Drug Topics* has dropped the beauty shops and barber shops from the list of outlets covered in its otherwise exhaustive surveys, and, although large quantities of these items are sold through these shops, no reliable figures are now available (1954). The trend is well established, however, in published estimates. For the year 1924, the percentage of the potential market using dyes was 6%; for 1950, 43%; for 1954, 76%. The notable increase in the latest figures has been ascribed to the development and promotion of the modern-type dyes for use at home.

With the exception of a few antiquated recipes, freely published in formularies, magazines, and other periodicals, all the best-known hair colorings in current use are proprietary products of which the exact composition is not published. Information on latest research and development must be sought in the patent literature and trade papers (57–66).

Hair Colorings

The hair colorings in general use fall into two main groups: (*1*) *temporary* colorings, comprising powders, crayons, and tinted rinses; and (*2*) *permanent* colorings, comprising natural organic substances (plant derivatives), metallic preparations, and synthetic organic dyes.

TEMPORARY COLORINGS

Powders. The use of powder for changing the color of the hair is now largely confined to theatrical make-up, masquerades, and pageants in which it might be required for historical costumes; otherwise it is limited to the occasional freshening of the wigs worn by judges and certain other participants in courts of law.

During the 17th and 18th centuries, when powders were commonly used as a mark of fine dress, the basis of a good product was wheat starch, ground very fine. Potato starch became popular later, and the basic starches were frequently adulterated with plaster of Paris, burnt alabaster, flour, and chalk (8).

The first colored powders consisted of starch with various percentages of burnt sienna, umber, or other pigments for brownish shades, and Chinese (India) ink for black. Pastel shades, popular during the 19th century, were made by adding other pigments, or by moistening the white base with solutions of dyes, and grinding the tinted mass after it dried. Genuine gold and silver powders, for which metallic powders of similar shades were later substituted, were also used on occasion.

Crayons, similar to the mascaro used as make-up for the eyes (see Vol. 4, p. 548), have been made in several handy shapes, offered primarily for retouching new growth of hair between applications of permanent dyes (24,34).

These colored crayons for the hair are made of mixtures of natural or (usually now) synthetic waxes, with a soap, such as triethanolamine stearate, into which dyes or pigments are thoroughly incorporated. They are generally offered in a good range of shades, simulating the average colors of natural hair, so that they will blend with other dyes that may be on the hair. The consistency of the finished product must be such that the color can be easily applied as the stick is rubbed directly over the hair, or transferred from the stick to the hair by a moist brush.

Colored rinses (also called tint rinses) for the hair were originally patterned on the colored rinses commonly used to restore or change the shade of lingerie, curtains, or other articles used in the household.

Tinted rinses are similar in composition to the proprietary acid rinses, used as accessories to a shampoo (see Vol. 12, p. 229). The base may be tartaric acid (adipic, citric, acetic, and other acids have also been used, alone or in combination), with which various water-soluble azo dyes are carefully blended. All dyes should be selected from the official list of colors suitable for cosmetics, as published by the Food and Drug Administration. Several other colors, not certified, are still used by manufacturers who have long found them to be both satisfactory and quite harmless. It must be understood, however, that any use of noncertified colors is always at the risk of the manufacturer.

Most lines of colored rinses are offered in twelve to sixteen shades, from golden- and silver-blond, through various reddish and brownish shades to black. The average range of shades can be produced from the certified colors in Table I (for complete list see Vol. 4, pp. 287–313):

TABLE I. Certified Colors for Hair Rinses.

FDA Designation	Common Name	FDA Designation	Common Name
FD&C Yellow No. 5	Tartrazine	Ext D&C Red No. 6	Rose Bengale TDK
FD&C Yellow No. 6	Sunset Yellow FCF	Ext D&C Red No. 8	Fast Red A
FD&C Orange No. 1[a]	Orange I	FD&C Green No. 2	Light Green SF Yellowish
D&C Orange No. 4	Orange II	FD&C Green No. 3	Fast Green FCF
FD&C Red No. 1	Ponceau 3R	FD&C Blue No. 1	Brilliant Blue FCF
FD&C Red No. 4	Ponceau SX	Ext D&C Blue No. 1	Methylene Blue
D&C Red No. 5	Ponceau R	FD&C Violet No. 1	Acid Violet 6B
D&C Red No. 13	Lithol Red Sr	D&C Brown No. 1	Resorcin Brown
D&C Red No. 22	Eosin YS	D&C Black No. 1	Naphthol Blue Black

[a] Reclassification as Ext D&C Orange No. 3 under consideration (1955).

Very few of these colors are suitable for use alone. To produce the desired tints, dilute solutions (1 gram/liter) should be tested, singly and in mixtures, on white wool

or hair and also on naturally colored hair of shades on which the rinses might appropriately be used (24,34,35,46).

In manufacturing these rinses, solutions of the colors—especially mixtures—must be thoroughly worked into the crystals of the acid. The finished product is usually sold in envelopes of cellophane or translucent, moistureproof paper, containing about 1 ounce. Some brands appear in capsules, compressed tablets, or solutions. When dissolved in 1 quart of hot water, the specified quantity of the product usually makes a solution in good concentration. This should be poured over the hair repeatedly until practically all the tint has disappeared from the water (53).

As originally presented, these colored rinses were intended to clear away any scum that might be left on the hair after shampooing it with soap (especially prevalent where hard water must be used), and impart tinted highlights. They became extremely popular, both for this purpose and for restoring faded, sun-bleached, or permanently waved hair to its natural shade. When the texture of the hair is normal, the tinted film deposited by these rinses usually disappears in the next shampoo. If the texture of the hair has been altered in any way, however, as in bleaching or permanent waving, it is usually more absorptive and the effect of a colored rinse is considerably more lasting. The use of wetting agents and other surface-active agents in synthetic ("soapless") shampoos also makes the hair more receptive and thus tends to make it retain these colors.

The addition of surface-active agents to the rinses themselves presents complications which should not be ignored by manufacturers and distributors of these products. Sodium lauryl sulfate, commonly used, tends to degrease the hair too thoroughly. The alkylated aryl sulfonates, besides making the color more lasting, also tend to coat the hair with a deposit which impairs texture and may interfere with other treatments, such as permanent waving and the use of penetrating (oxidation) dyes.

The amount of surface-active agents to be added to products of this type should be controlled most critically. Any excess may cause the coloring to diffuse within the mixture itself and thus not color the hair properly; or it may actually strip color from the hair.

Importance of Instructions. To protect consumers against unexpected results and possible disappointment from the use of supposedly temporary colored rinses, instructions for use should be most explicit and comprehensive. The warning on preliminary tests should be included as a protection for both distributors and consumers in those states where such a test is required before the application of all synthetic organic hair dyes.

Special Rinses. To neutralize the yellowish tinge that commonly appears in gray and white hair, rinses based on Methylene Blue, Acid Violet 6B, and water-soluble Nigrosine are available both as dry crystals and in solution. The accompanying instructions should ensure a concentration of no more than 0.001% in the solution as prepared for application to the hair.

To aid effectiveness, these bluing or "silvering" rinses are usually made with tartaric acid, or the other acids mentioned as suitable for lines of colored rinses (24,35).

For camomile and henna, used as "vegetable rinses" to impart a little color to the hair, see p. 170.

Miscellaneous Temporary Colorings. In addition to the rinses in various forms, already described, azo dyes have been combined with shampoos of different types. The earliest products of this kind used a base of neutral soap in small cakes, and were

applied like any soap for shampooing. As they proved to be unsatisfactory, they were soon abandoned.

Most "color shampoos" (all proprietary products) now are based on synthetic surface-active agents with wetting and detergent properties; for example, the sulfonated oils. The average line offers four to ten shades, in ½ to 2% concentrations (of color), suitable for blond, reddish, light- and dark-brown hair. Because the actual amount of color imparted is relatively slight, permitting the natural shade of the hair to show through it, the few colors in these lines seem to be satisfactory for hair of any shade.

PERMANENT COLORINGS

The use of temporary colorings for the hair is of relatively recent origin. The records of the ancient peoples indicate that they were mainly interested in preparations and treatments that could effect a permanent change in color. Dissatisfaction with the composition and effects of all available products at the time led Dr. Herman Beigel of London to publish (1869) the following "requirements of a good hair dye" (1):

(*1*) It must not be injurious to the general health.

(*2*) It must dye the hair, but not the skin.

(*3*) It must have no ill effect on the structure of the hair.

(*4*) It must not require a long time for the production of its effect.

Modern specialists now recognize three more requirements:

(*5*) It must have no irritating effect on the skin.

(*6*) It must produce shades that are natural in appearance and reasonably lasting.

(*7*) It must be compatible with other treatments, such as permanent waving.

The permanent dyes in general use, both in beauty shops and at home, are of three general types: plant derivatives, metallic preparations, and synthetic organic dyes.

Plant Derivatives. The earliest known hair dyes, natural organic substances obtained from plants, were used as infusions, decoctions, or packs. Many of the decoctions of woods are still utilized for the dyeing and blending of postiche (hair pieces), but, of all the vegetable substances used by the ancients, only henna and camomile persist in modern professional and amateur practice.

Henna. The first recorded user of henna as a hair dye was the Egyptian Queen Ses, mother of King Teta (Third Dynasty). The plant has always popularly been called *Egyptian henna*, although it is found abundantly also in Tunis, Arabia, Persia, India, and other tropical countries. It was commonly used by the inhabitants of all these countries to dye not only human hair but also the nails, the palms and soles of dancers, and the manes and tails of horses.

The henna plant is a shrub, *Lawsonia alba* Lam. or *Lawsonia inermis* L., similar to the familiar privet. It bears small, fragrant, greenish white flowers, but, as the only parts utilized for dye are the leaves and stems, the plants are frequently cut back. For infusions, used as rinses, the leaves are usually left whole, but in the more common commercial form of henna the leaves and stems are ground to a powder, about the color of dark mustard and with a characteristic earthy odor.

The active coloring principle in henna was called *lawsone* by Tommasi, who isolated it in 1916 and determined its chemical constitution to be 2-hydroxy-1,4-naphthoquinone, $C_{10}H_6O_3$ (see Vol. **11**, p. 419). Further definitive work on henna and lawsone was done by H. E. Cox. The extract is an orange-red dye, readily soluble in water, dilute alkalies, and acids. The true color can be seen best on white hair. Actually,

its coppery, carrot-red shade is the same on all hair of any shade, but it seems to impart different colors because of variation in the basic shade. The color of henna is developed best in an acid medium (10,34,35).

The principal advantage offered by henna as a modern hair dye is that it is harmless to the system and causes no irritation of the skin. The disadvantages are that the shades it produces are not altogether natural. For keratin (see Vol. **12**, p. 238; *Wool*), henna acts as a substantive dye. A few applications impart a slight amount of color to the entire hair shaft, but in continued use it seems to accumulate on the outside of the hair. If it is applied often enough, therefore, hair of any and all original shades can be brought to the same characteristic orange-red (53).

(*a*) *Henna rinse:* For a slight change of color, or to bring out highlights on dark hair, henna leaves are steeped in boiling water until all the dye is extracted. This solution is then poured several times over freshly shampooed hair.

(*b*) *Henna pack:* For a more decided, or more lasting, change in shade, powdered henna leaves are made into a paste with boiling water. This is applied to all the hair, which is allowed to remain covered and undisturbed until a test on a single strand shows that the desired shade has been attained. In subsequent treatments, the color can be kept uniform by applying the paste to only the new growth of hair.

(*c*) *Henna shampoo:* Because henna dye works best in acid mediums, many attempts to utilize it as a colored shampoo were ineffective. Sodium or triethanolamine lauryl sulfate mixed with a mild organic acid makes a satisfactory shampoo of this type, when freshly prepared. It is usually recommended for dark hair on which it may be desirable to bring out warm highlights. Instructions should always mention the limitations of such a shampoo, notably that repeated applications may deepen the coppery shade and act as a permanent dye.

For compound henna, see p. 176; for "white henna," see p. 185.

Camomile (chamomile). Another of the few plants that are still used for coloring the hair is camomile. Several varieties of related plants are found in Great Britain, western Europe, and the U.S., of which only two—*Anthemis nobilis*, called Roman camomile, and *Matricaria chamomilla*, called German or Hungarian camomile—are used to any extent (34,35).

The daisy-like, white and yellow heads of these flowers have been known and used for centuries as a drug, in poultices for external application, and as an infusion ("camomile tea") for internal discomfort. The coloring principle has been identified as *apigenin* (4,5,7-trihydroxyflavone), $C_{15}H_{10}O_5$, yellow needles, m.p. 347–8°C., both free and as a glucoside, found in an extract of the florets.

Like henna, camomile can be used as a rinse, a pack, or a shampoo (53).

(*a*) For the *rinse*, a strong infusion of either German or Roman camomile should be made with boiling water. While it is still comfortably warm, this liquid should be poured repeatedly over freshly shampooed hair.

(*b*) *Camomile pack.* As camomile flowers alone do not form a cohesive pack, they should be powdered, mixed (2 parts) with kaolin or fuller's earth (1 part), and made into a thin paste with boiling water. The shade produced depends on the original shade of the hair and the time of contact, and the change in color lasts considerably longer than the glints produced by a rinse (35).

As *manzanilla*, camomile packs have been intermittently popular with (normally dark) Spanish-American women who admire blond hair. In marketing mixtures of camomile flowers distributors should give adequate instructions for use and on the

results to be expected. Repeated applications of camomile on any shade of hair eventually bring out a brilliant chrome-yellow, similar to the coating commonly seen on lead pencils.

(*c*) *Camomile shampoo.* For a brightening shampoo on light hair, German camomile is usually preferred, both because it produces a slightly better color and because it is considerably cheaper than the Roman variety.

For a shampoo powder, 5% of camomile and 5% of a mild acid (adipic or boric) may be added to any acceptable "soapless" composition. For a liquid form, 10% of prepared camomile extract may be mixed with 30–40% of sodium or triethanolamine lauryl sulfate (30%) and 50–60% of distilled water. This is most effective, however, when freshly prepared (35).

To modify the harsh colors produced by either substance alone, henna and camomile are occasionally mixed in varying proportions. Packs of this type may be used to very good effect to produce a fair range of colors on hair of different basic shades.

Indigo (*C.I.* 1247) (see Vol. **7**, p. 814). Although it was known and widely used in various ways from earliest times, indigo is little used now as a hair coloring. The familiar blue dye, indigotin, $C_{16}H_{10}N_2O_2$, is obtained from several species of *Indigofera.* As woad, obtained from *Isatis tinctoria*, a similar blue dye was used by the ancient inhabitants of Britain to tattoo patterns on, or stain, their entire skin before going into battle (8,32,35).

The best source of indigo for the hair is *I. argentea*, long cultivated in Persia for this purpose, but it cannot be used alone. The dried and powdered leaves (known as *reng*) are either mixed with ground henna or applied alternately with henna, to produce a good black. Shades from light brown to black can be produced by varying the proportions of henna and reng.

Indigo seems to have no place in modern cosmetology.

Wood Extracts (see also *Dyes*, Vol. **5**, pp. 345, 352; *Tanning materials*, Vol. **13**, p. 585). Decoctions of woody fibers, bark, or nuts from several trees are also used as dyes. Of all that have been tried since earliest times only the following survive, and these are now used more for dyeing postiche (hair pieces) than hair on the head.

(*a*) *Brazilwood* (*Redwood, Pernambuco Wood*): Wood from *Cæsalpinia brasiliensis* or *C. echinata.* The active dyeing principle is *brazilin*, $C_{16}H_{14}O_5$, a yellowish color which in oxygen or with alkalies becomes the red dye brazilein, $C_{16}H_{12}O_5$. It is used in various combinations to produce warm brown shades (16,33,35).

(*b*) *Catechu* (*Gambier, Cutch*) (*C.I.* 1249): Name given to colored product of two distinct species—*Ouroparia* (*Uncaria*) *gambir*, which is yellow, and *Acacia catechu*, which is brown to black. The active principles in both are catechin (catechol), $C_{15}H_{14}O_6.4H_2O$, and catechutannic acid. One product or the other is used in combinations to produce all shades from blond to black.

(*c*) *Fustic*: The wood of *Chlorophora* (*Morus, Maclura*) *tinctoria*, a tree similar to the mulberry, common in the Western Hemisphere. The active principle is morin (2′,3,4′,5,7-pentahydroxyflavone), $C_{15}H_{10}O_7$; it also contains maclurin (morintannic acid), $C_{13}H_{10}O_6.H_2O$. Under different conditions and in various combinations, it produces yellow-to-brown shades. This dye is often called "old fustic" (*C.I.* 1232) (from Arabic, *fustuq*) to distinguish it from "young fustic" (*C.I.* 1231) (from Portuguese, *fustet*), obtained from an entirely different European tree, *Cotinus coggygria* (*Rhus cotinus*), which yields another dyestuff (31,35,54).

(*d*) *Logwood* (*Bluewood, Campeche Wood*) (*C.I.* 1246): The heartwood of *Hæma-*

toxylon campechianum L., a tree common in the West Indies and Central America. Its active principle is hematoxylin (hydroxybrasilin), $C_{16}H_{14}O_6 \cdot 3H_2O$, which is readily oxidized to hematein, $C_{16}H_{12}O_6$. It is specifically good for producing black and for drabbing or neutralizing reddish tones in the hair.

(*e*) *Nutgalls* (*Gallnuts*): Pathological excrescences on leaves, twigs, or other tissues of the white oak tree (*Quercus infectoria* or *Q. lusitanica*), caused by the invasion of bacteria, certain worms, or insects. These little "nuts" which are especially rich in tannin and gallic acid (*q.v.*), serve as a source of pyrogallol, and are priced according to the content of tannin. The European variety yields about 30%; the Turkish (Aleppo), 60%; and the Chinese (obtained from *Rhus semialata*, related to cashew nut), 70% or more. Nutgalls are of interest because they form the basis of "rasticks," a very ancient type of hair dye, still used in the Orient (see p. 173) (35,54).

(*f*) *Quercitron* (*C.I.* 1233): The inner bark of another species of oak tree (*Quercus tinctoria*), common in North America. Its active principles are quercetin (3,3′,4′,5,7-pentahydroxyflavone), $C_{15}H_{10}O_7$, and its 3-L-rhamnoside, quercitrin, $C_{21}H_{20}O_{11}$. This bark is usually combined with fustic and logwood to produce dark-brown shades.

(*g*) *Walnut*: The leaves of walnut trees (*Juglans cinerea, J. nigra, J. regia*), but more commonly the green nut shells, have been used from most ancient times as a source of brown hair coloring. The active principle is juglone (5-hydroxy-1,4-naphthoquinone (nucin), $C_{10}H_6O_3$ (see Vol. **11**, p. 419); pyrogallol is also believed to contribute to the dyeing property. Because the color produced on the hair is not lasting, walnut extract is now rarely used alone; the ground shells are usually mixed with other color-producing substances.

As the walnut tree was not native to England, and the relatively small growth of it there was cultivated for timber and for the edible nuts, quantities of the shells were among the earliest exports from the American Colonies, for the fabric-dyeing trade in England (30).

Pyrogallol (*q.v.*) (1,2,3-trihydroxybenzene, pyrogallic acid), $C_6H_3(OH)_3$. The effectiveness of many of the natural coloring substances used to produce brown shades of hair is due to the pyrogallol present or developed in one or another of the ingredients. Used alone, pyrogallol acts as a progressive dye. A freshly prepared aqueous solution gradually darkens when exposed to the air; the addition of dilute ammonia hastens the development of the color.

Pyrogallol itself (that is, the compound, not as nutgalls or walnut shells) was first used for dyeing the hair in 1846, and for many years it was a common ingredient of vegetable mixtures and also a developer for metallic dyes. Reports of irritation of the skin, and of toxic effects when it was taken internally, led to the banning or restriction of pyrogallol as a hair dye in several European countries. Various authorities seem to disagree on this point. The 0.5% solution suggested as safe is often ineffective as a developer, whereas the more concentrated solutions commonly used in dyeing processes in the trade seem to cause no untoward results. Pyrogallol is listed among substances that are harmful when and if they are absorbed by the skin; yet contents of 4–10% are found in recipes for many accepted antiseptic and medicinal products (54).

Pyrogallol has often been added to henna packs to take advantage of the strong dyeing property of the latter but produce brown shades. Without still other ingredients to fix the color, these so-called "vegetable packs" are usually unsatisfactory, because the brownish tinge soon wears off, leaving the characteristic red shade of the henna (35,53).

Rasticks; Mordants. To hasten the development of the desired shade or to modify it, the natural organic colorings have commonly been mixed with solutions of metallic salts. These adjuvants, so-called mordants, have been used in the dyeing of fabrics since the days of the early Egyptians. One of the earliest successful dyes for the hair was the *rastik* (from Turkish and Persian words for hair dye), made originally by roasting nutgalls, copper and iron filings, and a small quantity of oil in a copper vessel. The roasted mass was then ground, made into a paste with a little water, and this was applied to the hair for several hours. It produced a beautiful permanent black (32,36).

Variations have been introduced into this process, but the underlying principle is still the same; the occasionally weak organic dye is intensified and, by a choice of metallic salts, modified into a fair range of shades. Copper and iron sulfates and alum were the earliest recorded mordants. All may be found in products still in use, especially ferrous sulfate, which is commonly used with the wood extracts in dyeing postiche(16,33,35).

Since pyrogallol has been available most of the rasticks have been made from this, rather than from nutgalls or shells. Potassium dichromate, used for a few years to hasten the action of pyrogallol (and as an oxidizing agent with organic dyes), is now mentioned only in articles in medical literature. For the modern rasticks, see under "Compound hennas," p. 176.

Miscellaneous Plant Products. Among other plants commonly listed as sources of hair colorings are *rhubarb* and *sage*. The former has occasionally been combined with henna, black tea, and camomile. Its active principle is *chrysophanol* (chrysophanic acid, 1,8-dihydroxy-3-methylanthraquinone), $C_{15}H_{10}O_4$, which gives good blond shades, especially with alkaline mordants. Whatever its possibilities, it seems not to be utilized commercially (54).

Sage, prepared as an infusion ("sage tea"), is now considered antiquated, though it may still be used in homemade preparations. Its principal effect is to dull white hairs, making them less conspicuous, but long-continued application makes the hair look grayish and dingy.

Advantages and Disadvantages of Vegetable Dyes. The principal advantage in the use of vegetable dyes is that they are harmless to the system. (Synthetic pyrogallol should not be included with the natural vegetable products.) The disadvantages are in the relatively harsh and unnatural shades produced, especially after repeated applications; and in changes in texture whereby the hair becomes stiffer, more wiry, and occasionally brittle (53).

Metallic Hair Dyes. As hair colorings, metallic salts are almost as old as the plant derivatives. Both men and women in ancient Rome darkened their hair by passing through it a lead comb that had been dipped in vinegar. Many other metals have been used from time to time, and a wider variety of salts is still to be found in the European market than in the U.S. Because the metallic dyes are incompatible with permanent waving and oxidation dyes, the great increase in popularity of these two treatments has noticeably curtailed use of the metallic dyes by women. Large quantities of all types, however, are still used by men.

Most of the metallic dyes have been sold with the appeal that they are "not dyes—just color restorers for the hair." At one time many of these preparations were compounded by pharmacists and hairdressers, to be sold under their own name. The metallic dyes are almost never applied in modern beauty shops, but as "hair restorers" they are sold in retail stores for application at home.

The metallic dyes in the American market are based principally on (in order of prevalence) lead, silver, and copper. Nickel alone is rare, but it is found with silver; iron is found in most copper preparations. Bismuth (comparatively rare in the U.S.), manganese, and cobalt are fairly common in foreign products.

The old theory underlying the use of metallic dyes is that solutions of various salts act on the sulfur in the keratin of hair, thus forming a deposit of the corresponding sulfides. This seems not to be substantiated by more recent investigations and practical research. The fact that several applications may be required before any change in color is noticeable supports the idea that these products are restoring the natural coloring of the hair. The new substance, however, is merely deposited on the outside of the hair like a plating which, through the action of light and air or a developer, consists of an insoluble oxide, or sulfide, or both. The range of shades obtainable is necessarily restricted to the colors of the oxides and sulfides of the metals used.

Lead Dyes. Most of the "color restorers" based on lead consist of dilute solutions of lead acetate or nitrate. Many compositions call for the addition of finely powdered sulfur, glycerol, and either rose water or bay rum as perfume. All formularies, handbooks, and works of reference on cosmetics offer numbers of recipes for this type of product (3,6,9,12,27,36,49,54).

One long-established proprietary product is sold as two powders, to be added to water at the time of application. Newer variations are in cream form, to be applied like cream shampoos, in which surface-active agents are incorporated to ensure quicker development of color and some penetration of the hair. All lead dyes are classified as "progressive."

Ordinarily the color develops from dull yellow through greenish, violet, and mahogany shades to a dull black. As these products are to be applied "day after day until the desired shade is seen," the accumulated coating is likely to rub off on hatbands and bedding. Men should be warned against use of these "restorers" on the moustache because of the danger of taking the metallic compound internally.

Silver Dyes. The principle underlying the so-called restorers based on silver is twofold: (*1*) all silver salts darken on exposure to the light; (*2*) silver combines readily with protein, forming a brown stain.

In the oldest preparations, silver nitrate was used alone, in a dilute solution which was combed through the hair and allowed to remain undisturbed during exposure to strong sunlight. If the shade obtained was too light, the application of solution and exposure were repeated on successive days. Used in this way, silver dyes may be classified as progressive.

To hasten the action, silver dyes were offered in two bottles, one containing silver nitrate, the other containing a developer, such as sodium (potassium, ammonium) hydrosulfide or pyrogallol. With the former, silver sulfide is deposited directly on the hair; with the latter, there is believed to be double action, the silver salt acting as a mordant for the coloring property of the pyrogallol, and the latter serving to develop the silver.

Later improvements in these compositions added varying amounts of ammonia to the silver solution, thereby inhibiting certain proportions of silver and producing a fair gradation in shades. Sodium thiosulfate (photographers' "hypo") was adopted as a developer, presented either as a second solution or as a powder in packets or capsules.

As a precaution against deterioration, the silver nitrate should always be in a dark blue or amber bottle, closed securely against escape of ammonia.

Restorers of this type are classified as "instantaneous." For best effect, the hair must be absolutely clean, so it should be freshly shampooed and dried. The silver solution is combed through the hair first and distributed evenly; this is followed immediately by the solution of thiosulfate, which brings out the color.

In general, silver dyes are more satisfactory than those based on lead. The user may have trouble, however, after the first application, in the retouching of new growth of hair. Repeated applications to the same portion of hair cause the hair to become progressively darker and to develop an unpleasant metallic or iridescent sheen (53).

Recipes for silver dyes of all types are available in most of the standard works of reference (18,27,36,49,54).

Copper Dyes. The modern hair dyes based on copper have been evolved from the ancient rastiks, in that the same essential ingredients are combined in liquid form instead of powders. The earliest were in two bottles, one containing copper sulfate (with or without ammonia), the other containing either a hydrosulfide or pyrogallol as the developer. Like the older silver preparations, these were to be applied successively. Many of these were applied in hairdressing salons; and, because the pyrogallol was related to wood extracts, they were misrepresented to be vegetable products.

An improvement in copper dyes was offered by Schueller of Paris, in 1907, whereby the metallic salts (copper and iron) were combined in one bottle with both pyrogallol and, for example, sodium sulfite. This type of product starts to darken on the hair as soon as it is exposed to the air. Anything that remains unused must be carefully closed because it soon separates into a clear green supernatant fluid with a brown sediment (12,35,36).

By changing the composition or proportions of the metallic salts, some variation can be effected in the shade produced. One or two applications may be satisfactory, but repeated retouching, especially if any of the dye is allowed to run over previously treated hair, makes the hair a dusty, ugly black, and eventually harsh, stiff, and brittle.

Copper sulfate or chloride has occasionally been sold in a third bottle with proprietary products based on silver. This solution is recommended as a final rinse to cover the iridescent effect commonly seen on hair dyed with silver.

Miscellaneous Metallic Dyes. To produce a wider range of shades, and especially lighter shades, than is possible with the metallic dyes just described, the following metals have been employed from time to time, and may still be found in current proprietary products.

(*a*) *Bismuth*: First successfully employed by Naquet in 1881, to produce ash-blond and light-brown shades. Neutral bismuth nitrate, first dissolved in glycerol and then carefully diluted with water, can serve as a progressive dye; sodium thiosulfate is commonly offered in a second bottle as a developer. Combinations with silver nitrate act more quickly and produce more lasting shades. Bismuth citrate has also been suggested (6,12,32,36,49,54).

(*b*) *Cobalt*: Used with a developer (hydrosulfide or pyrogallol) to produce light-brown shades. First featured by Broux of Paris, the use of cobalt nitrate, either alone or in mixtures with silver and ammonium compounds, permitted the introduction of a full line of twenty shades of dyes, from blonds to black. The developer was pyrogallol with or without other phenolic compounds and iron salts (12,35,36,54).

(*c*) *Iron*: The least harmful to the hair, but also the least effective metal whose salts are used as hair dyes. In one of the oldest recipes, Galen recommended boiling iron in red wine. Ferrous sulfate was commonly employed in old progressive dyes

and also as the customary mordant with many natural dyes (wood extracts) for dyeing postiche. Used alone, iron salts produce unsatisfactory blond shades because they tend to darken; and the darker shades from more concentrated solutions are dingy, grayish, and fleeting. As modifiers in compositions with copper, cobalt, and other salts, ferrous sulfate and ferric chloride have been used for many years. As the developer for iron salts, pyrogallol has supplanted the evil-smelling hydrosulfides formerly used (9,49,54).

(*d*) *Nickel*: Occasionally found alone, but usually combined with silver, cobalt, or copper. Nickel nitrate produces fair dark-brown shades; ammonium hydroxide or carbonate is usually included, and the developer is usually pyrogallol (35,54).

(*e*) *Manganese*: Working on an entirely different principle; antiquated recipe still occasionally used in the home. A saturated solution of potassium or sodium permanganate, which is reduced to manganese dioxide in contact with organic matter, produces a good brown shade when it is combed through the hair. Attempts to revive interest in the use of this principle through offering the sodium salts (better shades) with sodium sulfide or pyrogallol as a developer have not been successful. In the trade and industry permanganates are considered quite obsolete (28,33,35).

(*f*) *Other Sulfides*: To widen the range of shades obtainable with metallic dyes, both stannic chloride and cadmium sulfate have been recommended and tried by various experimenters. Whatever the possibilities for golden shades and modifications of darker tones, they seem to have no practical application whatever at the present time.

Compound Hennas. The dyes called compound hennas were once considered sufficiently important to constitute a separate classification of modern hair dyes. They are now used so relatively little, however, that they need be considered merely another form of metallic dyes.

Theoretically, any mixture of henna with indigo, logwood, or any other natural coloring derived from plants is a compound henna, and many such mixtures have been prepared and applied as "vegetable packs" by hairdressers. The term came officially into prominence commercially about 1914 when both Broux and Schueller of Paris introduced to the trade a line of products, based on henna, which promised to produce any desired shade from blond to black (12,32,35,36).

The compound hennas immediately became popular because they answered the growing demand for "something like henna but not red," to be used in place of the synthetic organic dyes. Both the trade and the public were in fear of the latter because of increasing complaints of irritation following their use both by hairdressers and in the home.

These colorings are based on the formation of lakes from phenolic compounds, for example, aminophenol, pyrogallol, and hematoxylin, with salts of cobalt, copper, iron, and nickel. The preferred reducing agent is sodium thiosulfate. In the liquid preparations (Schueller), interaction of the ingredients is prevented by excess of the reducing agent; in the powdered mixtures, the reducing salt is packed separately, to be added as the paste is made with water (12,35,36).

Henna is the carrier for all the shades, but its carroty-red tone is successfully masked by additions of tannin, pyrogallol, nutgalls, lampblack, and other coloring agents.

These modern rasticks maintained their vogue for about twenty years. The more natural tints obtainable with the newer synthetic organic dyes drew many users away from compound hennas as well as from other metallic dyes; and the rapid increase in

permanent waving, which has been steady since 1934, has practically finished the use of them in the U.S.

Advantages and Disadvantages of Metallic Dyes. The principal advantage that can be claimed for metallic dyes is that, unless they are accidentally taken internally, by mouth or through abrasions in the skin, they are generally considered harmless to the skin and to the system.

The only dye permitted for use on eyebrows and eyelashes, under the Federal Food, Drug and Cosmetic Act in the U.S., is a solution (up to 5%) of silver nitrate with sodium thiosulfate as the developer. See also Vol. 4, p. 548.

The disadvantages of metallic dyes are numerous: the range of shades normally produced is limited to harsh dark browns and black; lighter shades darken unpredictably or fade; all metallic dyes deposit a plating on the hair which frequently causes unpleasant off-shades, and eventually makes the hair stiff and brittle. Because of abnormal changes in texture, such hair frequently is adversely affected by permanent waving (53).

Toxicity of Metallic Hair Dyes. Modern science, especially in the applications of biochemistry to medicine, has reappraised through tests in clinics and laboratories, many of the inherited notions about the toxicity of metallic compounds. It is now known that, in the low concentrations commonly used in hair dyes, there is practically no danger of absorption through the unbroken skin. The danger of cumulative effects through allowing the metallic compounds to enter the system by mouth still exists; hence the need for caution by men who might apply the so-called "color restorers" to the moustache.

Manufacturers and distributors of metallic dyes should ensure protection of users by most explicit instructions for applying their products. No authenticated case of poisoning from lead or copper dyes has been traced to any of these products when they were applied correctly. The pyrogallol commonly used as a developer has been alleged to cause allergic reactions in sensitive persons.

A statement common in the medical literature is that the application of silver dyes can cause the bluish-gray diffused pigmentation of the skin known as *argyria* (see Vol. **12**, p. 467). In two investigations all the authors admitted that they had copied the statement from other publications. The first case was traced (1928) to a man that had been dyeing his moustache (1874); the second case was traced (1942) to mistranslation of an article in a foreign journal (1924). There seems to be far less danger of argyria from metallic hair dye than from the silver compound commonly used as an antiseptic for mouth and throat.

Since 1887, copper and lead (along with arsenic, mercury, tin, zinc, and other metals) have been forbidden by law in Germany and Austria for use in cosmetic preparations. Most authorities in the field now feel that these restrictions should be reviewed in the light of modern developments in the industry, and possibly modified.

The Federal Food, Drug and Cosmetic Act imposes no restrictions on metallic hair dyes; but the Sanitary Code of the City of New York requires that all such proprietary products carry a statement that the product contains a metallic salt (unnamed) and that it must be used with care.

Synthetic Organic Dyes. Any classification of synthetic organic dyes contains also the azo and other dyes covered under "Colored rinses," but to those in the trade the term means the group of amines, aminophenols, and related compounds called "oxidation dyes" (also "amino dyes," "para dyes," and "peroxide dyes"). Because

these dyes are easily applied, produce natural-looking shades, and have no adverse effect on normal hair, they have almost entirely superseded the hennas in beauty shops and seem to be increasingly popular for use at home. Essentially the same compounds and compositions are available under many trade names; all are applied cold and all depend for development of the shade on hydrogen peroxide or some other noncontaminating compound that readily liberates oxygen. Many of the same compositions are used in the dyeing of furs. See also *Furs and fur processing*, Vol. **7**, p. 44; *Oxidation dyes*, Vol. **9**, p. 674.

History of Oxidation Dyes for Hair. The first of the amino dyes to be used on human hair was *p*-phenylenediamine (*q.v.*), $C_6H_4(NH_2)_2$. This compound had been described in 1863 by Hofmann, but its possibilities as a dye for hair, fur, and feathers were first made known in 1883, when a patent was granted to P. Monnet and Co., of Paris. Five years later the first of several German patents was granted, to E. (and/or H.) Erdmann, for the use of diamines, aminophenols, and related compounds in the dyeing of fur, hair, and feathers.

For the dyeing of living hair, the earliest method of applying *p*-phenylenediamine was in two steps: (*1*) wetting the hair with a 1–3% solution of the dye, made alkaline with caustic soda, sodium carbonate, or ammonia water; (*2*) applying oxidizing solution to bring out color. Many familiar oxidizing agents were used: ferric chloride, potassium dichromate and permanganate, hydrogen peroxide. It was soon found, however, that the best results were obtained with ammonia as the alkalizer and hydrogen peroxide as the developer, and by mixing the two solutions immediately before use.

The voiding of the German patents (1892–3) turned Erdmann against the promotion of *p*-phenylenediamine as a hair dye and prompted him to undertake intensive research for substitutes. He worked out a good code of safety regulations for workers in the fur dye industry, but supported a concerted effort on the part of physicians and scientists to have *p*-phenylenediamine banned as a hair dye. Because of accumulating reports on dermatitis from hair dyeing and on serious toxicity as shown in pharmacological investigations, the official pronouncement banning *p*-phenylenediamine from unrestricted retail sale in Germany and including it in the official list of poisons was made in 1906.

By this time, Erdmann had successfully introduced two new hair dyes for both hairdressers and the retail trade: one, a mixture of *p*-methylaminophenol sulfate (Metol), $HOC_6H_4NHCH_3 \cdot \frac{1}{2}H_2SO_4$, *p*-aminophenol hydrochloride, $HOC_6H_4NH_2.HCl$, *p*-aminodiphenylamine, $NH_2C_6H_4NHC_6H_5$, and sodium sulfite; the other, a mixture of the sodium salts of *p*-aminodiphenylaminesulfonic acid, $NH_2C_6H_3(SO_3H)NHC_6H_5$, and *o*-aminophenolsulfonic acid, $HOC_6H_4(NH_2)SO_3H$. A few years later (1911) another type of dye, a mixture of *p*-tolylenediamine, $CH_3C_6H_3(NH_2)_2$, and sulfites, was introduced by Colman and Loewy and widely publicized. See also Vol. **1**, pp. 739–40; Vol. **10**, pp. 379–80 (7,13,14,32,37).

Meanwhile, use of the amino dyes had continued unabated in France, and the French physicians who reported increasing numbers of "accidents" among those that had used *p*-phenylenediamine as hair dye were the first to recognize any connection between dermatitis or other unpleasant effects and a predisposition, personal susceptibility, idiosyncrasy, or (now) allergy in the individual. From France, through the activities of manufacturers and hairdressers, the amino dyes were introduced into England, other European countries, and North and South America.

Up to this time a few commercial products had been available in a limited range of shades, and most hairdressers had prepared their own solutions, mixing colors to meet the needs of individual patrons. In 1910, the first standardized product, accompanied by workable instructions for use, was offered in a range of eleven controlled, reproducible shades. This was the work of Gaston Boudou, a well-known hairdresser with salons in London and Paris, with the cooperation of Emile Rousseau, a chemist and pharmacist, and Raimond Sabouraud, an experienced dermatologist. The immediate success of this product led to an increase in 1917 in the number of available shades to eighteen, which fairly well simulated the average shades of human hair. The time for a treatment was cut by the addition of a little soap and ammonia to the solution of dye (38).

In 1911, following years of agitation by physicians, *p*-phenylenediamine was officially restricted in France. In the same year, however, Sabouraud, whose increasing clinical experience had convinced him of the importance of personal susceptibility or allergy in cases of dermatitis from the amino hair dyes, succeeded in publicizing the necessity for a preliminary test by those that wished to use

these dyes. This "skin test" was an application of the method of testing for susceptibility which had been introduced in 1895 by Josef Jadassohn, a dermatologist of Breslau, Germany. Considering the large numbers of applications of hair dyes, Sabouraud believed the percentage of susceptible persons to be relatively small, but in order to protect them his directions for making the preliminary test were disseminated widely both in scientific journals and in the public press (39,40).

Boudou's line of oxidation dyes, merchandised through an English company, was introduced into the U.S. in 1919. The type of dye was not new, as *p*-paraphenylenediamine and related compounds had been used in the U.S. by hairdressers and sold as a few proprietary products since the 1890's. The new line was immediately successful, both because of the superiority of the products and because both hairdressers and the public were reacting against the compound hennas then in vogue.

Research for Improved Products and Processes. Within a short time after the new line of oxidation dyes was introduced, cases of dermatitis were reported from all over the U.S. The American company immediately took steps to protect users of their products and to initiate intensive research toward improving both compositions and methods of application. The pioneer in all this work was Ralph L. Evans, a chemist of New York, then an instructor on the staff of Marston T. Bogert, in the Department of Chemistry at Columbia University. He first modified the compositions to inhibit the irritating effects of the *p*-phenylenediamine dyes and then, in 1924, introduced a new line of colorings without this ingredient. He standardized methods for applying the oxidation dyes, including requirements for a preliminary shampoo and pretreatment with hydrogen peroxide to make the hair more receptive to the dyes. Among other improvements were the establishing of strict specifications for raw materials and for hydrogen peroxide (5–6%, 17–20 vol.); and the development of products and treatments for removing old dyes so that prospective users of amino dyes could change from the coating varieties with the minimum of damage to their hair (15,44).

In 1926, Dr. Evans' company established the first center for formal instruction on hair, hair dyes, and dyeing methods; and a staff of well-trained technicians who carried this instruction to all parts of the country, through public and private demonstrations to the trade and in schools of general beauty culture.

Advantages and Disadvantages of Amino Dyes. Even in the earliest days, with all the impure materials, caustic oxidizing agents, relatively crude shades, and uncertain methods of application, it was obvious that the effects of dyeing hair with the new products were better than those obtainable with earlier dyes. The colorings penetrated the hair shaft instead of coating it, and when the excess was washed away, the hair retained its natural luster and was not adversely affected by curling irons. As compositions were improved and the range of shades was extended beyond those of dyed seal, red fox, and brown bear, it became obvious that any natural shade of hair, from palest blond to deepest black, can be duplicated with the amino dyes. For anyone with the requisite knowledge and technical skill they are easily applied.

It would seem, therefore, that the amino dyes meet the requirements of the "ideal dye" except for the one disadvantage of their irritating effects on the skin of allergic individuals. Although the importance of personal susceptibility and the benign nature of the condition in most cases were recognized in the earliest reports, it was many years before it was recognized that "hair dye poisoning" is simply dermatitis venenata (contact dermatitis). The amino dyes should thus be classified with poison ivy, and several other plants, chemicals, and other dermatitis-producing allergens (*q.v.*) (5,19,41,50,51).

Reports of death and of serious internal disturbances from *p*-phenylenediamine hair dye can usually be traced to medical writers who were not themselves investigators and who mistook early reports of troubles in the fur industry, or pharmacological studies on animals, as general truth. The bulk of adverse medical literature on *p*-phenylenediamine alone is impressive, but little of it is of value at this stage in the development of the whole broad field of oxidation dyes in cosmetics and cosmetology.

Searches in the literature are now best limited to publications by physicians and scientists who have both clinical experience and first-hand knowledge of contemporary procedures in the manufacturing and application of this type of product (15,22,43,48).

Forms of Oxidation Dyes. Regardless of the physical form in which the amino or oxidation dyes are offered to the trade and to the public, the underlying principle in all is the same. The materials for any single application are packaged in two units: one, containing the dye (commonly marked "A"); the other either a bottle of stabilized hydrogen peroxide (commonly marked "B") or a well-protected measured quantity of urea peroxide in tablets or powder.

These products may be in the form of:

(*a*) *Clear liquids*: The oldest form of the modern successful dyes. They remain thin clear liquids when mixed with the developer. Methods of application usually require a preliminary shampoo and pretreatment with hydrogen peroxide.

(*b*) *Shampoo tints*: Theoretically a combination of coloring and shampoo, which originated in Germany and were introduced into the U.S. from France and England in the early '30's. The first products were thickened with a simple fatty acid or (usually) a synthetic soap, and the (usually) dry oxidizer was added either directly or as a freshly prepared solution. This type of product offered few, if any, advantages over the preceding. The techniques of application were exactly the same, and most of the assorted surface-active agents, oils, and other materials, which have been added to various compositions in more recent developments, have not completely obviated the necessity for a good shampoo following the treatment with many products of this type.

(*c*) *Cream dyes*: The newest development, introduced from Germany in 1950. The dye is incorporated in a paste (or, later, a softer creamy base) with surface-active agents, essentially like those used in cream shampoos; sold in tightly sealed tubes from which a measured amount is squeezed out and mixed with hydrogen peroxide. As the technique for mixing and applying these products demands a good eye for color and a high degree of technical skill, they are intended for use only in beauty shops.

(*d*) *Miscellaneous*: New products based on amino dyes which seem to come and go from season to season. One type is a dilute solution of a dye in soap or synthetic detergent, to be mixed with some specified amount of peroxide. These are usually offered in only a few shades, intended to bring out highlights in the hair or to neutralize some unwanted off-shade.

French and German products when introduced to the American market are invariably based on *p*-tolylenediamine (*p*-toluylenediamine), because of the restrictions against *p*-phenylenediamine in Europe. The former base has been found to offer no advantages over the latter.

The amino dyes have been predominantly products intended for application by experienced and skillful hairdressers, but most of them have also been sold directly to consumers. In one product, introduced in 1950 exclusively for use at home, the dyes were combined with a relatively high percentage of surface-active agents and developed by strong hydrogen peroxide, which was activated by an enzyme catalyst. It was thus possible to avoid all preliminary treatment of the hair and shorten the time of application considerably for untrained users.

Composition of Modern Amino Dyes. Relatively little has been published on the composition of the modern oxidation hair dyes. All the good dyes in current use are proprietary products. Some of the recipes in newer formularies and handbooks

indicate the newer trends in composition, but others merely perpetuate the identity and quantity of ingredients in the most primitive of usable mixtures. Patents owned by various companies divulge the acceptable minimum; otherwise, all technical information is carefully guarded by the manufacturers, and is usually known outside only to their consultants and to their competitors (12,35,36,54).

If all hair that is to be dyed were gray and in good condition, the compounding of a good product would be a comparatively simple problem. The production of good hair dyes only begins with the blending of shades. Ideal colors on normal human hair in good condition may look entirely different on hair that has been permanently waved, bleached, treated with remedial preparations, even shampooed with different types of products and in different kinds of water. All these factors must be considered before any line of dyes is thought to be satisfactory (52).

Far from being the simple dye-alkali-oxidizer of the early days, the modern dye seems to be so compounded that it will not only color the hair but also cleanse and recondition it, and "take" properly with controlled development of the desired shade. Anyone that wishes to do research on hair dyes must, therefore, be familiar with many other types of contributory substances and compounds.

(*a*) *Dyes*: The range of actual or potential amino and related compounds now available should make it possible to reproduce all the average shades of human hair as well as many unusual ones. The eighteen standardized shades which served satisfactorily for about twenty-five years have been augmented to as many as thirty in some lines. In others, the number has been reduced to about a dozen average shades which can be modified to blend with intermediate tones.

Any shade of human hair from "tow" blond to darkest brown falls into two general classifications: *drab* or ashy tones, with neutral or silvery highlights; *warm* tones, with reddish (coppery) or golden highlights. Any line of dyes must be planned to meet the demands of these basic variations; hence the compounder must know how to produce natural-looking golden, silver, and ash blonds; golden, ash, and reddish light and medium browns; golden, coppery, and auburn reds; warm and dull dark browns; even a bluish and a dull black.

In compounding blond shades, the required preliminary bleaching of the hair must always be taken into consideration.

Table II, compiled from many sources, offers suggestions, from which any variety of combinations and modifications can be assembled (24,25,35,36,54).

Many beautiful shades may be spoiled through shampooing with the strongly alkaline soaps and water softeners required in regions where hard water prevails. The correcting of these "off-shades" has brought in a new group of colors in grayish tones which are to be mixed with, or applied over, the shade selected for a given head of hair.

The rapid increase in the use of synthetic detergents instead of soap for shampooing, in order to circumvent the unpleasant effects of hard water, has caused a corresponding increase in other effects in the hair. These, too, must be considered in the compounding and testing of many shades.

(*b*) *Adjuvants*: For various reasons mentioned above, it has become common manufacturing practice to "improve" a good dye solution by adding one or more substances with special properties. Small amounts of soaps, ammonia, and certain wetting agents will help dyes to penetrate the hair and "take" more quickly.

Everything to be added for any other purpose, such as a sequestering agent (*q.v.*),

TABLE II. Bases and Intermediates for Hair Dyes.

Black	Dark/medium brown	Light brown	Reddish	Blonds	Blue/gray; modifiers
p-Aminodiphenylamine	*p*-Aminodiphenylamine	*o*-Aminophenol	2-Amino-4-nitrophenol	*p*-Aminodiphenylamine-sulfonic acid	*p*-Aminodiphenylamine hydrochloride
p,p' - Diaminodiphenylamine	*o*-Aminophenol	*p*-Aminophenol hydrochloride	4-Amino-2-nitrophenol	4-Amino-2-nitrophenol	*N*-(*p*-Aminophenyl)-glycine
2,5-Diaminophenol-4-sulfonic acid	*p*-Aminophenol	*p,p'* - Diaminodiphenylamine	2,4-Diaminophenol	*p*-Aminophenol hydrochloride	2,4-Diaminoanisole
1,8-Diaminonaphthalene	*N* - (*p* - Aminophenyl)-glycine	2,4-Diaminophenol	4,6 - Dinitro - 2 - aminophenol	2 - Aminophenol - 4 - sulfonic acid	*p,p'*-Diaminodiphenylmethane
o-Phenylenediamine	*o*-Anisidine	2-Nitro-*p*-phenylenediamine	5 - Nitro-*m* - phenylenediamine	4 - Aminophenol - 2 - sulfonic acid	2,4-Diaminophenetole
p-Phenylenediamine	2,4-Diaminophenol	*m*-Phenylenediamine	4 - Nitro - *o* - phenylenediamine	5 - Aminophenol - 2 - sulfonic acid	1,5-Naphthalenediol
m-Tolylenediamine	*N,N*-Dimethyl-*p*-phenylenediamine	*p*-Phenylenediamine hydrochloride	2 - Nitro - *p* - phenylenediamine	2,5 - Diaminophenol - 4-sulfonic acid	*m*-Phenylenediamine
p-Tolylenediamine	*N*-(*p*-Hydroxyphenyl)-glycine	*p*-Tolylenediamine	2,4,6-Trinitroaniline	*N*-(2-Hydroxy-5-nitrophenyl)glycine	Pyrocatechol
	p-Methylaminophenol			*N*-(*p*-Nitrophenyl)glycine	Pyrogallol
	4-Nitro-*o*-phenylenediamine			*m*-Phenylenediamine hydrochloride	Resorcinol
	m-Phenylenediamine			*p*-Phenylenediamine sulfate	*p*-Tolylenediamine
	p-Phenylenediamine				

should be most carefully checked, both as to quality and as to quantity, to ensure that it is compatible and effective for the purpose intended. Sulfonated oils, for example, strip color from both natural and dyed hair; therefore, they must be used with caution. The alkylated aryl sulfonates are adsorbed on the hair and consequently may prevent adequate penetration of the hair for complete coverage or full development of the shade. Other surface-active chemicals make the hair feel harsh (almost metallic) and difficult to handle. The amount of adjuvant to be added should be kept at the minimum as even a slight excess of some substances may cause the dye to diffuse through themselves and not affect the hair at all.

Details of developments in this phase of research and activity on hair dyes should be sought in the appropriate patents and technical journals, and from the suppliers of raw materials (57–66).

(*c*) *Hydrogen Peroxide* (*q.v.*): Under normal conditions, hydrogen peroxide in a solution of 5–6%, generating 20 volumes of oxygen, is strong enough for the usual procedures in hair dyeing. *Even on normal hair the use of peroxide of 25 or 30 volumes*, or higher, may prove deleterious. It is even more damaging to hair that is not in good condition. If urea peroxide is to be used, special precautions should be observed; see "Solid hydrogen peroxide," p. 185.

(*d*) *Mordants*: There has been a revival of interest in combinations of various types of synthetic organic dyes with mordants, such as salts of chromium, cobalt, copper, iron, and other heavy metals. Although it might be possible to produce satisfactory shades of hair with these combinations, they represent a reversion to the older types of dyes with which the disadvantages outweigh the single advantage that some of them are nonallergenic (24,36).

Regulations Governing Amino Dyes. Always singling *p*-phenylenediamine from the large group of amino dyes, the medical authorities in the U.S. sought from time to time to have it banned from use as hair dye, or subjected to special control by the Food and Drug Administration. This was first proposed in 1924, but no action was taken. In 1926, the Health Department of the City of New York amended its Sanitary Code to prohibit the sale and distribution of cosmetic preparations containing *p*-phenylenediamine, lead, and mercury. This was never effectively enforced.

In the face of multiplying competitive lines of products and consequent rapid increase in the use of amino dyes, as well as a better understanding of the trouble caused by these dyes, in which none proved to be completely blameless, some of the authorities took a more lenient attitude toward them. Ethical manufacturers had for years included in the directions for use of their products the instructions for making the preliminary test for allergy; but the injunction was directed to those that knew they were allergic to foods, drugs, or other chemical substances. For better protection of all users, the Sanitary Code of the City of New York was again amended (1931) to make the preliminary test mandatory, twenty-four hours before any general application of any amino dye; and to require all beauty shops where such dyes were applied to post a sign acknowledging the use of amino dyes and stating the requirement for the test.

The Federal Food, Drug and Cosmetic Act, as enacted in 1938, specifically requires every user to make the preliminary skin test before every application of any hair dye that contains amino compounds; and also prohibits all use of dyes of this type on the eyebrows and eyelashes. Most of the State laws governing foods, drugs, and cosmetics include similar regulations for use of amino hair dyes; a few have extended them also to hair colorings based on the certified colors.

Responsibility in claims for damages in the now occasional cases of dermatitis from an application of hair coloring is now determined by whether or not the preliminary test was made as prescribed by law.

Bleaching Agents

Although the effect of a bleaching agent is the subtraction, rather than the addition, of color, bleaches for the hair are often classed with colorings because they do, in fact, cause a change in shade. Like dyes, bleaching agents are among the oldest products on which there is a practically continuous record.

Early Bleaches. Primitive recipes for bleaching the hair were common in Rome during the two centuries that bridged the beginning of the Christian era. The Roman ladies greatly admired the golden hair of many of the captives brought from northern countries and tried to imitate it. Native minerals such as rock alum, quicklime, crude soda, and wood wash, occasionally combined with old wine (or dregs of wine) and water, served as favorite "blond washes." These preparations were left on the hair overnight or for several days, and the resulting reddish-gold shades were usually considered satisfactory. If the hair happened to be completely destroyed, the ladies frequently demanded that the hair be shorn from the captives and made into wigs for them (8,32,33).

Renaissance Recipes and Practices. As cosmetic treatment was considered a legitimate part of medical practice until about the end of the 16th century, all the famous old books of medical (and other) "secrets" contain recipes for bleaching the hair. The alum, ashes, borax, niter, crude soap, and soda of the earliest mixtures were still used, but always with decoctions of various plants. Commonly found are birch bark, broom, celandine, lupine, mullein, myrrh, saffron, stavesacre, and turmeric; old wine and dregs of wine are also mentioned (8,27,49,54).

To produce the beautiful golden red ("Venetian blond") shade of hair immortalized by the great artist Titian, the Venetian ladies sponged and combed a solution of soda (or rock alum, black sulfur, and honey) through their hair, spread it over the broad brim of a crownless hat, and let it dry in the sunlight. This treatment was introduced into France late in the 16th century by Marguerite de Valois, and with slight modifications it remained for over two hundred years the acceptable method for producing blond and reddish shades of hair for the relatively few that desired them (32,53).

Chemical Bleaches. Although the fading of colors on exposure to air and sunlight had long been recognized, the slow action and uncertain results of molecular atmospheric oxygen made continued utilization of it impractical by the 19th century. When interest was revived in bleaching the hair—after two centuries of perukes and powder and a period of disfavor for all red shades of hair—many oxygen-releasing compounds were available for testing.

For use on living human hair, a chemical bleaching agent must be nontoxic, mild in action, and free of harmful residue. These requirements rule out many effective oxidizing agents; in fact, they narrow the possibilities to sodium hypochlorite and hydrogen peroxide (and sources). As the former is not suitable for the bleaching of animal fibers, use of it in cosmetology is limited to the removal of dye stains (see p. 187). The reducing action of sulfur dioxide is also utilized to a limited extent (35).

Hydrogen Peroxide (*q.v.*). The most satisfactory bleaching agent for human hair is hydrogen peroxide, because after its available oxygen has been released nothing but water remains. Although discovered in 1818, it was not adopted by hairdressers until some time after it had proved its worth in several branches of the textile industry. The bleaching of hair was first demonstrated through the collaboration of Leon Hugo, a Parisian hairdresser, with E. H. Thiellay, a chemist, during the Paris Exposition of 1867. Its popularity spread rapidly in Europe and in the U.S., and by the turn of the century hydrogen peroxide had superseded everything used previously for bleaching human hair.

For this purpose, the preferred peroxide was for many years that produced from

barium peroxide; that made electrolytically is now more commonly used. "Drug store peroxide," a 3–4% solution, generating 10–12 volumes of oxygen, is commonly used for bleaching the hair at home, but for more rapid action the 5–6%, 17–20 vol. solutions are generally used in beauty shops. These are sufficiently strong for all practical purposes; the solutions of 30 volumes or more, recommended for certain treatments, offer no advantage and may actually harm the hair.

To maintain the desired quality, solutions of hydrogen peroxide must be stabilized with chemicals; acetanilide, dilute acids, *p*-hydroxybenzoates, sodium stannate, or stannic hydroxide may be used. To aid in preventing deterioration through carelessness, dealers in supplies for beauty shops recommend that peroxide be bought in one-pound bottles, rather than larger containers.

Action of Peroxide on Hair. In practice, the peroxide solution is activated by the addition of ammonium peroxide (28%, 0.880 sp.gr.), usually 15–20 drops to the ounce of peroxide. The ammonia should always be used sparingly; too much may cause reddish tints to develop (53).

In the simplest method of bleaching, the hair should be well shampooed and dried, and the peroxide solution applied to the full length of it, strand by strand. The bleaching action, which oxidizes the color to lighter shades, can be continued as long as desired by keeping the hair saturated with the peroxide; and it can usually be stopped at any stage by copious rinsing with hot water. No second shampoo is required.

By experimenting with different proportions of peroxide and ammonia and times of contact a wide variety of beautiful shades of hair is obtainable. Other conditions being constant, any hair can be kept the same shade by periodically applying the same bleaching mixture for the same length of time to only the new growth of hair as it appears. Repeated application to the same portion of hair leads to serious damage to the texture of the hair and the familiar strawlike, overbleached appearance.

As the lightest obtainable shade with hydrogen peroxide is always yellowish, the whitish "platinum blond" shade requires a rinse with a dilute solution of Methyl Violet, Methylene Blue, or Nigrosine (24,35,53).

Bleaching Products and Treatments. In addition to solutions of hydrogen peroxide, which are marketed under many proprietary names, some of the other commercial forms are:

(*a*) *Solid Hydrogen Peroxide*: Tablets made of peroxide and urea; or mixtures of sodium perborate and, for example, tartaric acid. These are to be dissolved in water at the moment of use.

Any package that contains urea peroxide (see Vol. **10**, p. 82), to be made into a solution before being added to a dye solution, should carry instructions that only distilled water should be used for this purpose and that contact with metals should be avoided in preparing it. As a protection for both distributor and user, a date of expiration should be stamped on the package.

(*b*) "*White Henna*": A trade term for magnesium carbonate (with or without sodium perborate or other compounds), to be mixed with hydrogen peroxide and ammonia and applied in the same manner as the clear liquid. The alleged advantage is that the paste "stays put"; but the white obscures the development of the shade, and the treatment requires a second shampoo (35,53).

(*c*) *Oil Bleach*: Ammonium oleate, sulfonated olive or castor oil, to be mixed with peroxide at time of use (24).

(*d*) *Peroxide Shampoo*: In beauty shops, this is usually a mixture of hydrogen peroxide and soap solution. Proprietary products may be mixtures of wetting agents and sodium perborate. In selecting synthetic surface-active agents for such products, the pH must be taken into consideration (53).

Blanching of Hair. Besides the golden red and yellow shades of hair, obtainable with hydrogen peroxide, there has been an intermittent and sporadic demand for some means of turning mixed gray hair an even snowy white. For such a treatment, the reducing action of sulfur dioxide has been recommended.

The blanching effect of the fumes of sulfur dioxide on animal fibers has been utilized since at least the time of Pliny, for he recorded that the Romans exposed their woolen fabrics to the smoke from burning sulfur in order to whiten them. Later writers mention a mixture of sulfur and lye, used similarly.

According to more recent suggestions, the hair should be thoroughly washed and dried, saturated with a warm concentrated solution of potassium permanganate, and allowed to dry again. It is then saturated with a water solution of sodium thiosulfate, slightly acidified with sulfuric acid. When the brown color produced by the permanganate becomes appreciably lighter, the hair should be thoroughly rinsed with water. It is said that by repeating this double application a few times the hair can be made snow-white. For this treatment, the concentration of the two solutions must be most carefully controlled, or the hair may be badly damaged (28,35,49).

Efforts in research on a safe and sure means of blanching hair should be both esthetically and commercially profitable.

Dye Removers

In the long succession of products and treatments for the hair, dye removers came very late. Most of the "decolorizers" mentioned in a few publications before 1925 consisted of hydrogen peroxide or a hypochlorite, either of which was ineffective or disastrous on dyed hair. In that year, however, coincident with the intensive promotion and wide acceptance of the new American amino dyes, there was a spontaneous demand, both from hairdressers and from the public, for products and treatments by which dyed hair could be cleared of the hennas and metallic "restorers" and converted to the new dyes.

The truth of an axiom, then being taught to hairdressers, soon became obvious: There is no single safe quick-removal process for all old dyes. Many compounds were tried, for example, oxalic and citric acids, iodine and potassium iodide, potassium cyanide; but all were discarded as unsuitable or unsafe.

Because there will always undoubtedly be persons who wish to change from one type of hair coloring to another, that is, from the metallic to the oxidation dyes, there is a need for research on safe and effective dye removers. Any product of this kind should always be accompanied by explicit instructions for applying it over different types of dyes; and especially for simple tests by which the user can check progress toward the results desired (53).

Hot Oil Treatments. For the preliminary treatment of stubborn metallic ("coating") dyes, the hair may be soaked in a mixture of mineral and vegetable oils and heated by slipping strands of it through an iron. A marcel iron, a pressing iron (as

used for paper curls), or a metal pressing comb, such as Negroes use for straightening the hair, may be used. The hair is then rubbed with a towel and thoroughly shampooed.

This treatment seems actually to soften the coating on the hair so that much of it can be removed mechanically without causing breakage. It should be repeated until a test with the new product shows that the latter can be safely blended into the previously dyed hair (53).

Sulfonated Oils (see Vol. **3,** p. 240; Vol. **13,** p. 514). At any time, sulfonated oils must be applied to the hair with caution because they strip the natural color from it and may bring out unpleasant streaks. Many dye removers consist of sulfonated (usually castor) oils, with or without salicyclic acid or other substances of specific properties. After being applied they may be heated with irons, with an electrically wired cap, or any other convenient device.

An advantage of this type of product is that it is miscible with water or hydrogen peroxide, and thus may be used to remove (or lighten the color of) penetrating dyes.

Other possibilities are:

Sodium Hydrosulfite, $Na_2S_2O_4$ (see Vol. **13,** p. 427). Sodium hydrosulfite is the basis of several proprietary dye removers. Although they are most effective with the dyes based on certified colors, they are recommended also for lightening the shade of amino dyes, and especially for removing dye stains from the skin.

Sodium Thiosulfate, $Na_2S_2O_3$ (see p. 104). A 5% solution, acidified with 2% of sulfuric acid, has also been recommended for removing stains.

Sodium Formaldehydesulfoxylate, $NaSO_2CH_2OH$ (see Vol. **13,** p. 428). This compound has been successfully adopted from the textile industry for these purposes.

Testing of Products

Continuous research for improved products has greatly simplified the testing of hair dyes and related cosmetics.

Chemical Tests. Although the number of proprietary hair dyes on the market is bewildering, familiarity with the physical appearance of the various types described is the first long step toward identifying them. Simple qualitative tests will easily disclose the constituents of metallic dyes. Hair dyed with an unknown product can be incinerated, and the residue analyzed by usual procedures (10,11,21,22,48).

Confusion between plain and compound henna, for example, can be resolved by burning a sample of hair to ash. An earthy odor and the absence of residue would indicate the plant product; a dark residue could be tested for copper and iron. A complete testing program for samples of dyed hair was devised by Evans in 1925, and widely utilized in early educational programs (53).

Official tests for identifying the oxidation dyes, especially in combinations, have been published by the Cosmetics Division of the Food and Drug Administration (60).

The hydrogen peroxide furnished to manufacturers and distributors of hair dyes is now reliably uniform and uniformly good. In any emergency, the volume content could be quickly checked with a "peroxometer," adapted by Evans from a ureometer —a J-tube, to be filled with ammoniated copper sulfate, and marked so that the amount of oxygen liberated by 1 ml. of hydrogen peroxide can be read directly in milliliters of gas in the long arm. A newer device for the same purpose is like a hydrometer for specific gravity, calibrated for direct reading of volume-content.

Biological Tests. Despite the generally broader enlightenment now on the nature of the dermatitis caused in allergic individuals by some of the oxidation dyes, many elaborate programs of biological and pharmacological tests on the internal effects of these dyes (especially *p*-phenylenediamine) on small animals are still conducted from time to time. Carefully controlled programs of tests for external effects on large numbers of human beings of all types and under all conditions would help to establish the actual percentage of sensitive individuals, and thus resolve much of the long-standing doubt and fear of these valuable chemical products (43,51).

Clinical Tests. The clinical testing of any new hair dye is of the utmost importance to both manufacturer and user. There must be some assurance that the proposed product really is a good hair dye; that is, that it will give good results, not only of itself, but also in combination with other customary treatments. For example, it should not be considered sufficient just to produce good colors on cut swatches of hair before embarking on a long and expensive program of biological tests. The researcher should have the further assurance that his product will withstand permanent waving of hair on the living head, and average shampooing with a wide variety of modern products (52).

Bibliography

(1) Beigel, H., *The Human Hair*, Renshaw, London, 1869.
(2) Bennett, H., ed., *The Chemical Formulary*, Chemical Publishing Co., N.Y., Vols. I–IX 1933–50.
(3) Bennett, H., ed., *The Cosmetic Formulary*, Chemical Publishing Co., N.Y., 1937.
(4) *Bundesratsbeschluss*, Berlin, February 1, 1906.
(5) Cathelineau, H., *Bull. soc. franç. dermatol. syphilig.*, **6**, 16 (1895); **9**, 29 (1898).
(6) Cerbelaud, R., *Formulaire de Parfumeric*, Vol. III, Cerbelaud, Paris, 1936.
(7) Colman, J., and Loewy, A., *Deut. med. Wochschr.*, **37**, 926 (1911).
(8) Cooley, A. J., *The Toilet in Ancient and Modern Times*, Hardwicke, London, 1868.
(9) Cooley, A. J., *Handbook of Perfumes and Cosmetics*, Lippincott, Philadelphia, 1873.
(10) Cox, H. E., *Analyst*, **54**, 694 (1929); **58**, 738, 743 (1933); **59**, 3 (1934); **60**, 350 (1935).
(11) Cox, H. E., *Analyst*, **60**, 793 (1935).
(12) Durvelle, J.-P., *Nouveau Formulaire des Parfums et des Cosmetiques*, Desforges, Paris, 1930.
(13) Erdmann, E., *Z. angew. Chem.*, **18**, 1377 (1905).
(14) Erdmann, E., *Z. angew. Chem.*, **19**, 1053 (1906).
(15) Evans, R. L., *Proc. Sci. Sect. Toilet Goods Assoc.*, **No. 10**, 9 (1948).
(16) Foan, G. A., *The Art and Craft of Hairdressing*, 3rd ed., N. E. B. Walters, ed., Pitman, London, 1950.
(17) Forker, H., *Arch. Gewerbepathol. Gewerbehyg.*, **6**, 275 (1936).
(18) Gastou, P., *Formulaire Cosmetique et Esthetique*, Baillière, Paris, 1913.
(19) Goodman, H., *Cosmetic Dermatology*, McGraw-Hill, N.Y., 1936.
(20) Greenberg, L., and Lester, D., *Handbook of Cosmetic Materials*, Interscience, N.Y.-London, 1954.
(21) Griebel, E., *Z. Untersuch. Lebensm.*, **70**, 61 (1935).
(22) Hanzlik, P., *J. Ind. Hyg.*, **4**, 386, 448 (1922).
(23) Harry, R. G., *Cosmetic Materials*, Leonard Hill, London, 1948.
(24) Harry, R. G., *Modern Cosmeticology*, Chemical Publishing Co., N.Y., 1947.
(25) Heilengotter, R., *Am. Perfumer Essent. Oil Rev.*, **63**, 345 (1954).
(26) Ingram, J. T., *Brit. J. Dermatol. Syphilis*, **44**, 422 (1942); *Lancet*, **2**, 239 (1935).
(27) Joseph, M., *Handbuch der Kosmetik*, Von Veit, Leipzig, 1912.
(28) Klein, F., *Die moderne Kosmetik*, Carsten, Berlin, 1919.
(29) Lucas, A., *Ancient Egyptian Materials and Industries*, 2nd ed., Longmans, Green, London, 1934.
(30) McDonough, E. G., *Truth about Cosmetics*, Drug and Cosmetic Industry, N.Y., 1937.
(31) *Merck Index*, 6th ed., 1952.
(32) Monsegur, P. A., *Hair Dyes and Their Application*, Osborne, Garrett, London, 1915.
(33) Müller, F., *Der moderne Friseur*, Killinger, Berlin, 1927.

(34) Poucher, W. A., *Perfumes, Cosmetics and Soaps*, Vol. I, 5th ed.; Vols. II and III, 6th ed., Van Nostrand, N.Y., 1941, 1942.
(35) Redgrove, H. S., and Foan, G. A., *Hair Dyes and Hair Dyeing*, revised by H. S. Redgrove and J. Bari-Woollss, Heinemann, London, 1939.
(36) René le Florentin, *Cosmetiques et Produits de Beauté*, Desforges, Paris, 1938.
(37) Richter, P., *Monatsh. prakt. Dermatol.*, **24**, 25 (1897).
(38) Rousseau, E., *Les Teintures Capillaires à la p-Phenylenèdiamine*, LeGrand, Paris, 1914.
(39) Sabouraud, R., *La Clinique*, **6**, 694 (1911); N.Y. Herald (Paris ed.) November 20, 1911.
(40) Sabouraud, R., *Presse méd.*, **32**, 819 (1924); *Tiba*, **2**, 729 (1924).
(41) Sabouraud, R., *Diagnostique et Traitement des Affections du Cuir Chevelu*, Masson, Paris, 1932.
(42) Sainz de Aja, A., *Actas Dermo-Sifilog.*, **16**, 55, 148 (1924).
(43) Schwartz, L., and Barban, C. A., *Arch. Dermatol. and Syphilol.*, **66**, 233 (1952).
(44) Snell, F. D., *J. Soc. Cosmetic Chemists*, **2**, 43 (1950).
(45) Tests; Symposium, *J. Soc. Cosmetic Chemists*, **2**, 277 (1951).
(46) Thomssen, E. G., *Modern Cosmetics*, 3rd ed., Drug and Cosmetic Industry, N.Y., 1947.
(47) Toilet Goods Association, *Standards*, N.Y., 1953.
(48) Tzank, A., *et al.*, *Monde méd.*, **47**, 889 (1937); *Bull. soc. franç. dermatol. syphilig.*, **44**, 998 (1937); **46**, 879 (1939).
(49) Truttwin, H., ed., *Handbuch der Kosmetik*, 2nd ed., Barth, Leipzig, 1924.
(50) Wall, F. E., *J. Tech. Assoc. Fur Ind.*, **5**, 118 (1934).
(51) Wall, F. E., *Am. Perfumer Essent. Oil Rev.*, **40**, No. 1, 35 (1940).
(52) Wall, F. E., *Proc. Sci. Sect. Toilet Goods Assoc.*, **No. 5**, 28 (1946).
(53) Wall, F. E., *The Principles and Practice of Beauty Culture*, 2nd ed., Keystone Publications, N.Y., 1954.
(54) Winter, F., *Handbuch der gesamten Parfumerie und Kosmetik*, Springer, Wien, 1949.
(55) Winter, F., *Die Technik modernen Kosmetik*, Springer, Wien, 1949.
(56) Winter, F., *Haarfarben und Harfärbung*, Springer, Wien, 1930.

JOURNALS

Cosmetics

(57) *Alchimist*, Boechout, Belgium.
(58) *American Perfumer and Essential Oil Review*, New York.
(59) *Drug and Cosmetic Industry*, New York.
(60) *Journal of the Association of Official Agricultural Chemists*, Washington, D.C.
(61) *Journal of the Society of Cosmetic Chemists*, Detroit.
(62) *Manufacturing Chemist and Pharmaceutical and Fine Chemical Trade Journal*, London.
(63) *Perfumery and Essential Oil Record*, London.
(64) *Proceedings of the Scientific Section of the Toilet Goods Association*, New York.
(65) *Soap and Chemical Specialties* (formerly *Soap and Sanitary Chemicals*), New York.
(66) *Soap, Perfumery and Cosmetics*, London.

Cosmetology

(67) *American Hairdresser and Beauty Culture*, New York.
(68) *Modern Beauty Shop*, Chicago.

Dermatology

(69) *Archives of Dermatology and Syphilology*, Chicago.
(70) *British Journal of Dermatology*, London.
(71) *British Medical Journal*, London.
(72) *Journal of the American Medical Association*, Chicago.
(73) *Journal of Investigative Dermatology*, Baltimore.

FLORENCE E. WALL

TIRES. See *Rubber compounding and fabrication*, Vol. 11, p. 938.

TITANIUM AND TITANIUM ALLOYS

Titanium, Ti, atomic weight 47.9, atomic number 22, is in the fourth group of the periodic table above zirconium and hafnium, which it resembles in many properties. Horizontally it is between scandium and vanadium. The most abundant isotope is Ti^{48}, which comprises 73% of naturally occurring titanium. Others are Ti^{46}, Ti^{47}, Ti^{49}, and Ti^{50}, which comprise 5–8% each. See also *Titanium compounds*.

Discovery of the element is generally attributed to Gregor in 1791. Titanium occurs widespread in the earth's crust, being about one-tenth as abundant as iron and 600 times as abundant as copper. The first approach to the isolation of the pure metal was made in 1887 by Nilson and Peterson who succeeded in preparing a metal 94.7% pure. Approximate physical and chemical properties of pure titanium are given in Table I.

TABLE I. Approximate Physical and Chemical Properties of Titanium.

Appearance	Dull silvery, metallic
Density	4.54 g./cu.cm.
M.p.	≈1680°C.
B.p.	>3000°C.
Vapor pressure	≈12 microns at melting point
Crystalline form	Hexagonal close-packed transforming at 880°C. to body-centered cubic
Sp. heat	0.13 cal./(g.)(°C.)
Latent heat of fusion	96 cal./g.
Linear coefficient of expansion	$\approx 8.5 \times 10^{-6}$ per °C.
Electrical resistivity	$\approx 56 \times 10^{-6}$ (ohm)(sq.cm.)/(cm.)
Modulus of elasticity	$\approx 15 \times 10^{6}$ p.s.i.
Corrosion resistance	Aqueous chlorides—excellent Oxidizing acids—good

In spite of its wide occurrence, titanium has not been used as a structural metal until very recently, because of the difficulty of extracting it from its ores. Although it has many desirable properties for certain uses, the metal was not commercially available until 1948 and then only in small quantities at high prices. During 1954, titanium metal production was expanded at a phenomenal rate, despite continuing high prices. This expansion was the result of properties that make the metal unique for certain applications in military aircraft. An estimate of U.S. production is given in Table II.

TABLE II. Titanium Metal Production.

Year	U.S. production, tons
1948	10
1949	25
1950	75
1951	495[a]
1952	1075[a]
1953	2240[a]
1954	7200[b]

[a] Reported by the U.S. Bureau of Mines.
[b] Installed capacity completed by year end, excluding Bureau of Mines pilot unit.

It is expected that the price of titanium metal sponge will decline steadily over the next several years as a result of expansion by several U.S. producers. The price remained at $5.00 per pound from 1948 until early 1954 when one producer reduced the price about 8%. Later in 1954 the same producer reduced prices to about 13% below the initial $5.00 level.

The major property or combination of properties responsible for the meteoric growth of titanium metal is its high strength-weight ratio, particularly at somewhat elevated temperatures, as shown in Figure 4. It is the belief of many in the industry that the future market, particularly the civilian or commercial market, must depend on exploitation of the favorable corrosion resistance pattern of titanium. Other properties of interest are the high melting point, low thermal conductivity, and low coefficient of expansion of titanium and its alloys. In general, it appears that titanium alloys containing less than 10% of other metals will be required for strength-weight applications. For corrosion resistance, in such applications as chemical plant equipment, it appears that commercially pure titanium metal may have satisfactory mechanical properties. A summary of the physical and mechanical properties of both commercially pure and alloyed titanium is given in Tables VII and VIII. Many of these tables and a portion of this discussion are based on reference (26).

Analysis. A sensitive qualitative test for titanium comprises addition of hydrogen peroxide to solutions. Depending upon the concentration of titanium, the color developed by hydrogen peroxide varies from pale yellow to deep red-orange. Chromium, vanadium, and molybdenum may interfere. They produce blue, brownish-red, and yellow colorations, respectively. If their presence is suspected, the original sample is subjected to fusion with a mixture of sodium carbonate and sodium nitrate. The melt is then leached with hot water and the residue is dissolved in sulfuric acid. The peroxide test is then made on the resulting solution.

Titanium may be determined gravimetrically and colorimetrically, but the method most widely used in industry is the volumetric method (37) in which the sample is fused with potassium bisulfate, the fused mass dissolved in hydrochloric acid, carefully reduced by means of amalgamated zinc shot in a Jones reductor, and titrated with ferric alum in the presence of alkali thiocyanate indicator to a permanent straw-color end point. Although iron is often present, particularly in ore samples, it does not interfere in the ferric alum titration, since ferric iron is reduced along with the titanium during passage through the Jones reductor. Interfering elements, chromium, molybdenum, tungsten, and vanadium, may be removed from titanium solutions by precipitation of titanium with sodium hydroxide and hydrogen peroxide.

Ores

The principal ores of titanium are ilmenite, theoretically $FeO.TiO_2$, and rutile, TiO_2. Ilmenite is found in beach sands and in rock deposits associated with iron. Rutile is much less abundant; the principal source is certain Australian beach sands.

Ilmenite derives its name from the Ilmen mountains in the Ukraine, where it was first discovered as a massive rock ore. The principal sources today are the beach sands of Travancore, India, and ancient inland beaches in northern Florida. Massive rock titanium-bearing iron ores are found in the Adirondack Mountains and eastern Quebec. The former ore is produced by the National Lead Company at its MacIntyre mine; the latter is beneficiated by the Quebec Iron and Titanium Corporation to produce titanium dioxide -- rich slag and by-product pig iron.

Ores are also found in Norway, Brazil, Ceylon, Columbia, Uruguay, Newfoundland, and many other foreign countries. In this country ores are found in many states including New York, Florida, Virginia, California, Oklahoma, Arkansas, Wyoming, and Georgia.

A list of typical ore compositions is given in Table III.

TABLE III. Typical Titanium Ore Compositions.

Ore	Type	TiO_2, %	Fe, %	FeO, %	Fe_2O_3, %	V_2O_5, %	CaO, %	MgO, %
Indian ilmenite	Beach sand concentrate	60	25	10	25	0.4	0.3	1.2
Ceylon ilmenite	Beach sand concentrate	55	31	19	24	0.5	0.2	0.8
Florida ilmenite	Ancient beach sand concentrate	64	21	5	25	—	—	—
Adirondack ilmenite	Rock concentrate	45	35	38	7	—	—	—
Norway ilmenite	Rock concentrate	44	35	35	11	0.3	0.2	3.0
Canadian ilmenite	Rock concentrate	39	36	29	19	—	0.1	0.1
Canadian ilmenite	Rock slag beneficiate	72	6.7	6.8	—	0.5	1.4	4.7
Australian rutile	Sand concentrate	96.6	0.6	0.8	—	0.6	—	—

Preparation of Titanium Sponge

Early attempts to recover pure titanium from oxide ores by conventional smelting methods were unsuccessful. Several investigators produced and characterized impure materials in the belief that they had isolated pure titanium, thereby creating confusion and false notions regarding the metal's properties.

At elevated temperatures titanium metal has great affinity for oxygen, nitrogen, carbon, and hydrogen and can hold limited quantities of these elements in solid solution without formation of a second phase. These contaminants dissolve interstitially within the lattice without replacing titanium atoms of the lattice. Small amounts of such interstitial contaminants, less than 1%, render titanium metal brittle and useless. This fact explains the principal difficulty in the winning of titanium metal and accounts for the early failures.

Titanium dioxide can be partially reduced with carbon at high temperatures but attempts to complete the reduction result in formation of carbide. Titanium dioxide can be reduced by magnesium metal at red heat to a composition approximating $Ti_{14}O$. Calcium is more effective, and can give titanium metal containing only several tenths of 1% oxygen, but although the heat of formation of CaO is 151.7 kg.-cal. per gram mole, and that of TiO_2 is only 112 per oxygen atom, complete oxygen removal does not occur. This demonstrates the inherent stability and high heat of formation per atom of small amounts of oxygen in solid solution in titanium.

Essentially all the titanium produced today is produced from titanium tetrachloride. Titanium tetrachloride is produced by chlorination at red heat of titanium oxide ores mixed with carbon. The fact that titanium tetrachloride is a liquid which boils at 136 °C. permits purification by fractional distillation. In 1910, Hunter produced small amounts of ductile metal by sodium reduction of titanium tetrachloride in a small bomb constructed to withstand high pressure at red heat. Metal of the highest purity has been produced by Van Arkel and others by decomposition of titanium tetraiodide vapor on a hot filament under reduced pressure.

In 1940 Wilhelm F. Kroll obtained a patent for reducing titanium tetrachloride with magnesium metal at atmospheric pressure and at red heat in the presence of a noble gas such as helium or argon (48). The Kroll process was further developed by the U.S. Bureau of Mines at its experiment station at Boulder City, Nevada. Much of the impetus behind the recent growth of titanium should be credited to this agency and to F. S. Wartman who pioneered in ductile metal production.

The original process developed by the Bureau of Mines employed reduction of titanium tetrachloride by magnesium metal under helium on a scale of about 100 lb. The bulk of the by-product magnesium chloride was drained from the reactor as a liquid (m.p. 712°C.). The reactor was then cooled and transferred to a large lathe on

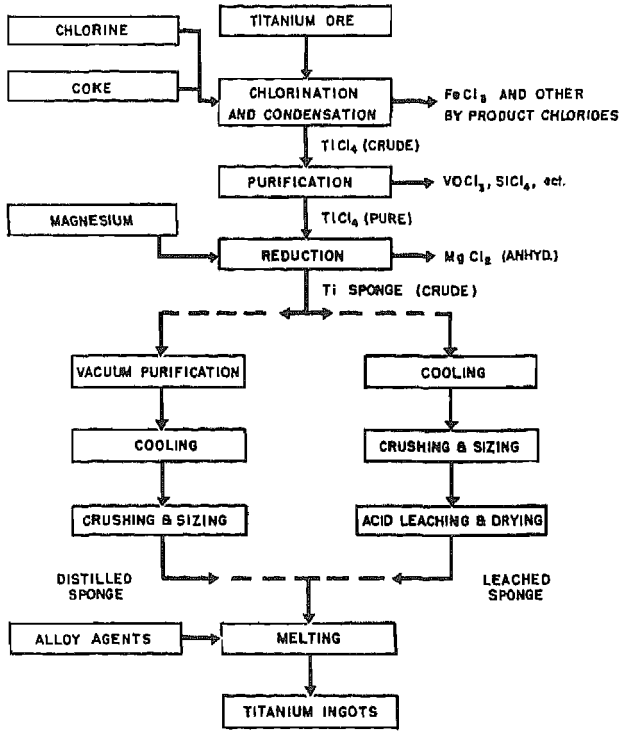


Fig. 1. Flow sheet.

which it was cut open and the crude metal removed as chips by boring. The crude metal chips contained unreacted magnesium metal and undrained magnesium chloride. These contaminants were leached out with dilute hydrochloric acid at room temperature. The leached chips were then ball-milled to a 35-mesh powder which was cold-pressed at 50 tons per square inch to form "green" compacts. These compacts were sintered at red heat under vacuum to volatilize residual contaminants and the hydrogen picked up during the leaching step. The sintered compacts were then hot worked, often in steel sheaths to exclude the atmosphere, to produce wrought metal for testing and evaluation. These developments were outlined in Bureau of Mines reports (43).

The process used at present by U.S. producers also employs magnesium reduction of titanium tetrachloride. Batches of metal weighing up to 3,000 lb. are produced. The crude metal is purified by volatilization of residual magnesium and magnesium

chloride at 900–1000°C. under high vacuum (see *Vacuum technique*) or by leaching with dilute acid. The purified sponge is generally sold to melters in the form of ½-in. lumps. A generalized flow sheet is given in Figure 1. Typical analyses are shown in Table IV.

TABLE IV. Typical Compositions of Commercial Titanium Sponge.

Component	Composition, %	
	Vacuum purified	Aqueous acid leached[a]
Ti	99.5	99.3
Fe	0.25	0.15
O_2	0.10	0.10
N_2	0.03	0.03
C	0.03	0.03
Mg	0.05	0.30

[a] Early product of U.S. Bureau of Mines.

Many millions of dollars annually are being spent by a number of industrial and government laboratories in an effort to develop a basically improved process for low-cost titanium. Sodium reduction of titanium tetrachloride is planned by one U.S. and by one British producer.

Potentially low-cost electrolytic processes have been announced on several recent occasions but have yet to become important. Perhaps the most significant factor in the development of an economical electrolytic process is that titanium must be deposited from a fused salt at a temperature far below its melting point. Under these conditions it has been difficult to produce massive metal, rather than fine particles, which can be withdrawn from the cell without excessive surface contamination and loss of electrolyte. Electrolysis of fused potassium fluotitanate, K_2TiF_6, is receiving considerable attention.

There is still much room for improved engineering and cost reduction in processes employing titanium tetrachloride and a reducing metal. The development of a process having low labor and low maintenance requirements and low capital investment per daily ton could result in great expansion of the titanium industry.

Consolidation and Fabrication

Titanium sponge (or scrap) cannot be melted by conventional techniques commonly employed for ferrous and nonferrous alloys. The high reactivity of the molten metal requires an inert blanket of a helium-group gas or vacuum to eliminate contamination with nitrogen and oxygen. Protective layers of flux are inadequate because of the adverse effects of even minor quantities of atmospheric gases. In addition, no refractory which is completely inert to molten metal is at present available. Even stable oxides such as thoria result in appreciable oxide contamination. The search for a suitable refractory is receiving much attention.

Powder Metallurgy. Initial efforts to bypass the high reactivity of molten titanium led to an extensive evaluation of powder metallurgy by the U.S. Bureau of Mines. Granular metal, scrap, or sponge may be pressed into compacts at pressures of 30–50 tons/sq.in. If appreciable quantities of volatiles such as magnesium, magnesium chloride, or hydrogen are present they can be removed by vacuum sinter-

ing (1×10^{-4} mm. at 1000°C. for 10–16 hours). High vacuum at temperature is necessary to reduce the volatiles to an acceptable level. Compacts may then be forged and rolled by conventional techniques. Low-volatile sponge containing less

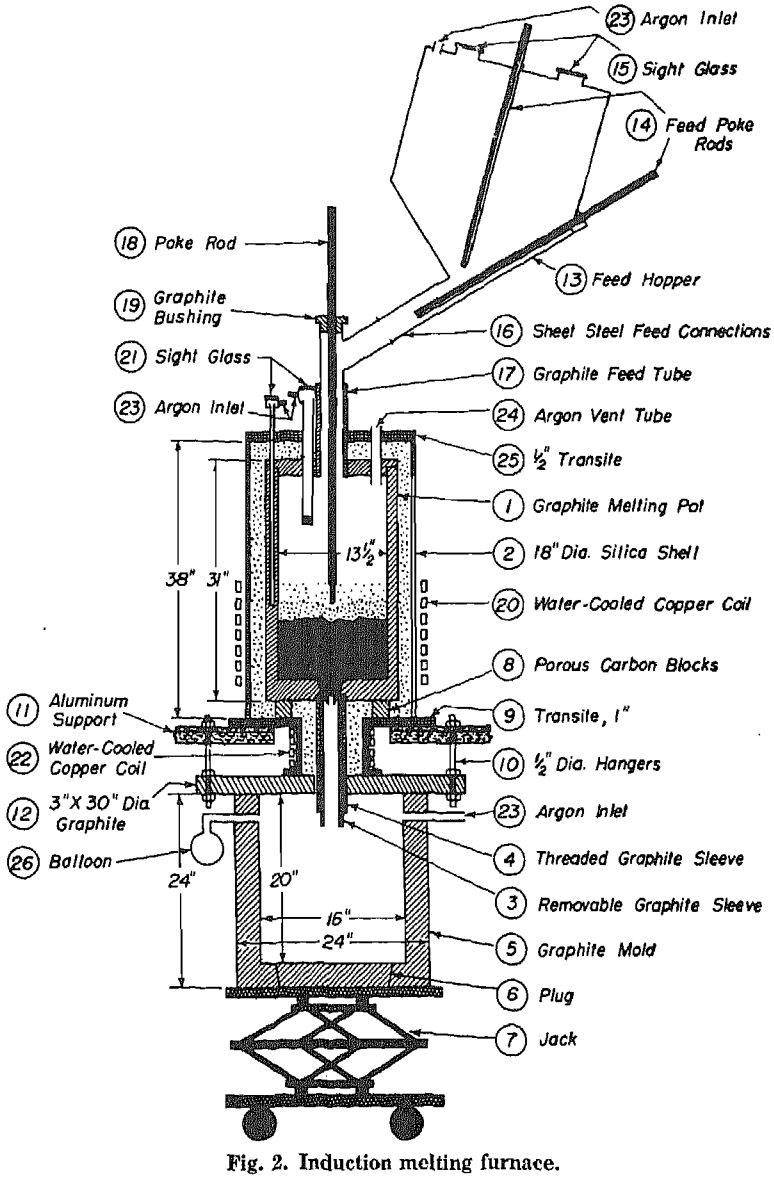


Fig. 2. Induction melting furnace.

than 0.1% magnesium and 0.01% hydrogen by weight does not require the extended vacuum sintering. Small specialty parts such as porous filter disks are manufactured by this technique.

Induction Melting. Of all the crucible refractories evaluated, only graphite has found even limited commercial application. This method has the inherent weakness of introducing 0.3–0.8% carbon into the melt resulting in undesirable effects on physi-

cal properties such as impact strength. Precipitated titanium carbide, which occurs at about 0.2% carbon and above, greatly increases the difficulty of fabrication by welding and machining. The major advantage of this technique is that the entire furnace charge is molten at one time, resulting in homogeneous alloys and permitting

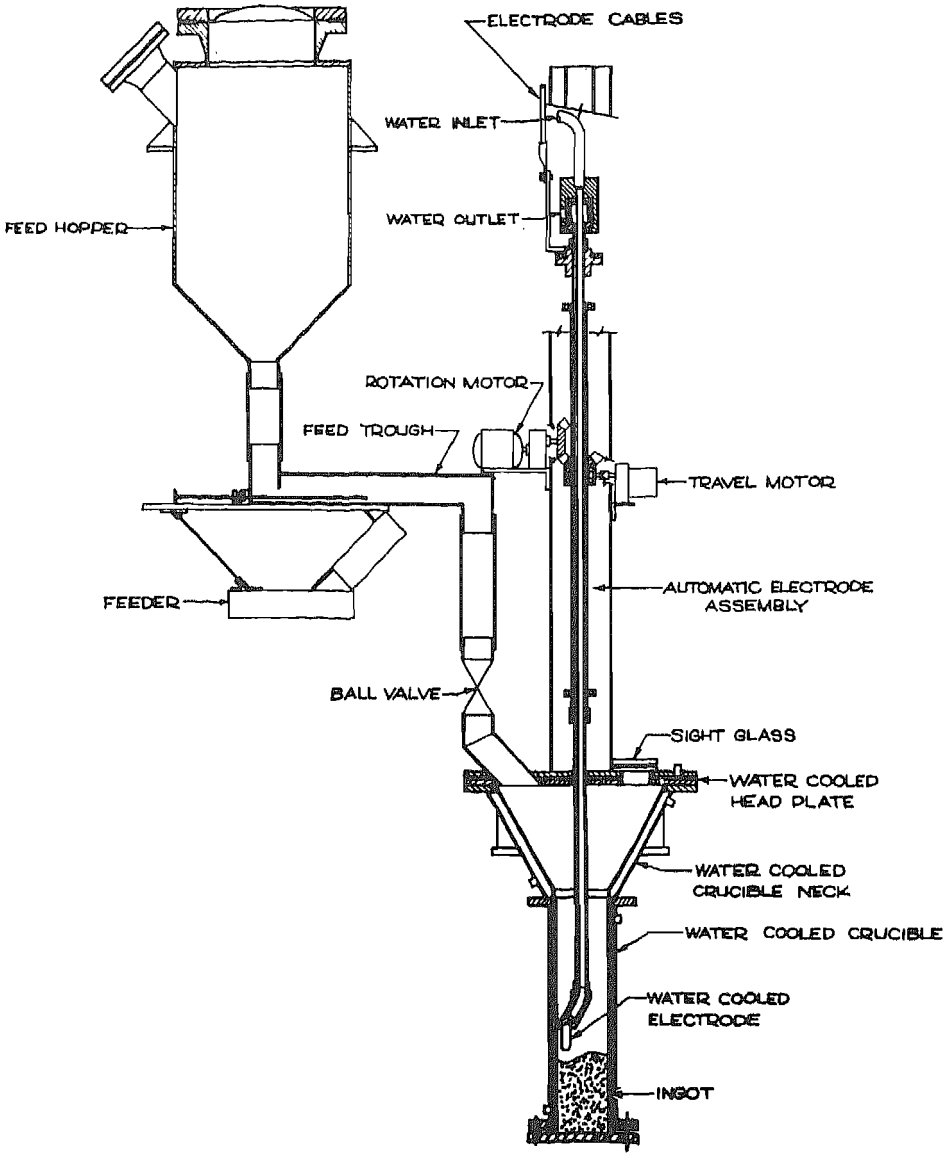


Fig. 3. Arc melting furnace.

the recycling of massive scrap. In the production of large forgings where relatively low ductility and toughness can be tolerated, this method has found limited application. Ingots up to 650 lb. in weight have been cast in furnaces such as that shown schematically in Figure 2.

Cold-Mold Arc Melting. Almost all titanium metal produced is melted in

water-cooled copper arc furnaces. Kroll was the first to apply this technique to titanium although it had previously been used for other refractory metals. The basic principles are quite simple. Heat is supplied by a d.c. arc struck between a cathode of tungsten, carbon, or titanium and the charge, which is contained within a water-cooled crucible. The crucible is securely sealed and filled with argon or helium to prevent atmospheric contamination. As the charge melts, a thin film of metal solidifies against the water-cooled crucible and serves as the real container for the liquid pool. A semidiagrammatic outline is shown in Figure 3.

This method has the basic advantage of reducing the amount of carbon or tungsten introduced to less than 0.2%, and when consumable electrodes of pressed titanium sponge are utilized as the electrode, these contaminants can be eliminated. Unfortunately only a relatively small pool of metal can be maintained molten at any one time and the production of large homogeneous alloy ingots is, therefore, a complex problem.

With permanent carbon or tungsten electrodes, titanium sponge and alloying agents must be carefully added, since only a small portion of the ingot exists as a homogeneous melt at any instant. With consumable electrodes a more extensive liquid pool can be maintained and somewhat better homogeneity results. Another advantage of consumable electrodes, when melting low-volatile commercial sponge, is an improved ingot surface and, therefore, a smaller scrap loss. A technique of producing an initial ingot of small diameter and subsequently remelting, using this as a consumable electrode feed for a second larger furnace, has recently been commercially utilized and further improves homogeneity. Continuous melting and withdrawal of arc-melted ingots has also been employed on a limited scale.

Ingots up to 4000 lb. have been produced by arc melting and the homogeneity of fabricated metal has greatly improved with increasing size.

Skull Melting. The use of thick skulls or shells of titanium to contain large molten pools of metal is under development in numerous laboratories, and small castings with properties similar to those of wrought metal have been produced. However, no large commercial exploitation of this technique is as yet reported. Heat is supplied by arc or carbon resistor and the skull is maintained by taking a large heat loss through the furnace hearth. This method offers a solution to the problem of scrap recovery, for which the cold-mold method is ill-adapted.

PRIMARY FABRICATION

While sponge or molten titanium reacts rapidly with gases of the atmosphere at elevated temperatures, consolidated metal can be heated in conventional electric, gas-, or oil-fired furnaces and forged in air without unusual precautions. This allows the manufacture of semi-fabricated products by forging, rolling, etc., on conventional mill equipment for stainless steel. A scale quickly forms at elevated temperatures on the surface of the metal which is fairly adherent and partially resistant to further oxidation. While the initial film is primarily oxide, gradual diffusion of both oxygen and nitrogen into the base metal occurs as the temperature is increased. In forms of appreciable cross section this effect is not significant since the hardened layer is negligible, but for very thin sections, such as thin-walled tubing and foil, inert-gas or vacuum heating may be required. Forging, rolling, and heat-treatment practice are tailored to minimize the effect of this phenomenon on finished parts.

Forging. Titanium and its alloys have found widespread evaluation as forged

turbine compressor blades, forged disks, pierced and forged rings, contour-forged compressor blanks, and miscellaneous open and closed die forgings. Titanium can be heated in electric, oil- or gas-fired furnaces. Temperatures in the range of 790–980°C. are used in forging titanium and its alloys. Alloys usually require temperatures about 25°C. higher than commercially pure grades. Titanium and its alloys move slowly under the hammer and more blows are usually required for a given reduction than for stainless steel in its forging range. Better results are obtained if a heavier hammer than that used for stainless is employed. The heated metal flows well and under proper conditions will fill the die cavity.

Rolling. Sheet bar of commercially pure titanium which has been ground or hot-chipped to remove defects can be hot rolled at temperatures of 730–820°C. In the production of thin sheets on hand mills, double and pack rolling is practiced. In rolling, alloys usually require a higher temperature than the commercially pure grades.

Cold rolling can be accomplished on conventional equipment and with conventional methods. As the strength level of metal is progressively increased by alloying, cold rolling becomes more difficult. Very pure titanium, such as that produced by the iodide process, can be cold reduced 98% but commercial grades are usually limited to 25–60% reduction.

Descaling and Pickling. Titanium metal and its alloys may be descaled by several conventional procedures. Mill and anneal scale is usually removed in a sodium hydride bath (see Vol. **9**, p. 7). Metal can be subsequently brightened by an acid dip. Unnecessarily prolonged exposure must be avoided in either step to minimize hydrogen contamination.

Virgo salt baths (fused sodium hydroxide and sodium nitrate) are also utilized. A maximum limit of 510°C. must be observed since explosive reactions between titanium and the bath have been observed above this level.

SECONDARY FABRICATION

Machining, Grinding, and Sawing. The physical properties of titanium give rise to special problems in machining and related operations: (*1*) The metal and its alloys seize and gall upon other metals and hard substances. This is well illustrated by the fact that it is possible to mark glass with moistened titanium. (*2*) It work-hardens rapidly and glazes when light cuts are attempted. (*3*) The low thermal conductivity results in high temperatures at the cutting edge with welding of the tool and part. (*4*) Scale formed during heating is hard and abrasive. (*5*) The low modulus requires firm back-up to prevent deformation. This cannot be over-emphasized, and heavy machines should be used. (*6*) Chips curl away from the tool at an abnormally sharp angle resulting in high stress concentration.

It must be emphasized that this is a new material of construction and that conventional procedures are not adequate. All normal shop operations can be carried out, however, with experienced personnel and proper technique. In brief, adequate coolants, slow speeds, sharp tools, and proper tool angles are essential.

Joining. Since titanium reacts rapidly with oxygen, nitrogen, and water vapor at elevated temperatures to produce hard and brittle alloys, care must be exercised in joining operations, particularly where a liquid phase is formed. Fortunately, inert arc welding supplies the required protective atmosphere.

Commercially pure metal can be fusion-welded successfully, although alloys pose serious problems. Two phase, alpha-beta alloys (see p. 206) usually suffer from a

brittle zone of little or no ductility, apparently as a result of recrystallization and grain growth, or beta decomposition products. These effects also occur with commercially pure metal but ductility is not seriously impaired. The use of unalloyed titanium as filler rod for alloys results in a diluted weld zone and improved ductility, particularly if controlled cooling is possible. Weldable single-phase alpha alloys containing aluminum and tin are marketed at present (1954).

Spot welding of commercially pure titanium and many of the alloys is readily carried out with good results. Joining of titanium to dissimilar metals by this technique has not been satisfactory since brittle welds result.

For brazing, all oxide films must be removed first and subsequent exposure to air should be prevented. Varying success has been reported in brazing titanium to itself and to other metals; successful joints can be produced but only under carefully controlled conditions. A brittle transition zone occurs if diffusion of the brazing alloy is allowed to take place; rapid operation at the minimum practical temperature, therefore, is indicated.

Sheet Forming. Many of the early difficulties in the forming of titanium and its alloys were due to the poor quality of available sponge at that time and to inhomogeneous ingots. As sponge quality and melting and fabricating techniques have improved, many of the original shortcomings have disappeared. Lack of homogeneity remains, however, as a major problem to the fabrication industry and extensive research is under way to improve uniformity.

In general, formability of titanium is influenced by the following characteristics: (*1*) high yield strength; (*2*) limited ductility at room temperature; (*3*) sensitivity to strain rate; (*4*) anisotropy; and (*5*) notch sensitivity. Commercially pure titanium is similar in forming to ¼ hard stainless, and titanium alloys to ½ or full-hard stainless steel. Work-hardened titanium is difficult to form and suitable alloys of corresponding strength levels are preferred.

Properties of Titanium and Titanium Alloys

The purest form of titanium is produced as a crystal bar by thermal decomposition of titanium tetraiodide, although no extensive commercial adaptation of this method has yet been made. Present commercial production is by magnesium reduction of titanium tetrachloride and it should be noted that commercially pure titanium is actually an alloy, although as manufacturing methods improve it may be possible to produce commercial metal approaching that obtained from titanium tetraiodide. Table V compares the properties of titanium obtained from the iodide with commercially pure metal consolidated from Kroll-process sponge.

TABLE V. Comparative Properties of Iodide and Kroll-process Sponge Titanium.

Property	Iodide	Kroll-process
Hardness, Brinell	55–95	120–200
Ultimate strength, p.s.i.	35–50,000	40–100,000
Yield strength, p.s.i.[a]	15–25,000	30–80,000
Elongation, % in 2 in.	40–70	20–40

[a] 0.2% offset.

Table VI compares the properties of titanium with those of other metals.

TABLE VI. Physical Properties of Titanium Compared with Other Metals.

Property	Commercially pure titanium	Aluminum 75-ST-6	Magnesium AZ-31A	Stainless steel AISI 302	Monel
Melting range:					
°C.	1680	476–638	565–632	1400–1420	1300–1350
°F.	3056	890–1180	1050–1170	2550–2600	2370–2460
Density, g./cu.cm.	4.5	2.80	1.78	7.93	8.84
Crystal structure type	H.C.P.[a] below 1615°F., B.C.C.[c] above 1615°F.	F.C.C.[b]	H.C.P.	F.C.C.	F.C.C.
Lattice constant, A.	2.9505 4.6833	4.0413 (Al)	3.2033 (Mg) 5.1998	—	3.541
Thermal conductivity: cal./(sec.)(sq.cm.)-(°C./cm.)	0.036	0.29	0.23	0.039	0.062
B.t.u./(hr.)(sq.ft.)-(°F./in.)	105	845	672	113	180
Thermal expansion (32–212°F.)	5.0×10^6	12.9×10^6	14.5×10^6	9.6×10^6	7.8×10^6
Sp. heat, cal./g./°C. or B.t.u./lb./°F. at room temperature	0.130	0.23	0.25	0.12	0.13
Electrical conductivity, % of IACS[d]	3.1	30.3	18.5	2.3	3.5
Electrical resistivity at 20°C.:					
Ohms-cir. mil/ft.	370	34.6	56.0	435	290
Microhms-cm.	61	5.75	9.3	72	48.2
Tensile modulus of elasticity, p.s.i.	15.5×10^6	10.4×10^6	6.5×10^6	28×10^6	26×10^6
Torsional modulus of elasticity, p.s.i.	6.5×10^6	3.8×10^6	2.4×10^6	12.5×10^6	9.5×10^6
Poisson's ratio	0.34	0.33	0.35	0.30	

[a] Hexagonal close-packed.
[b] Face-centered cubic.
[c] Body-centered cubic.
[d] International annealed copper standard (see Vol. 4, p. 429).

Table VII gives the mechanical properties of commercially pure titanium and Table VIII similar data for alloys. Physical properties are outlined in Table IX.

Summarizing, the harder commercially pure grades of titanium are approximately equal in strength-weight ratio to magnesium and aluminum alloys at room temperature. Titanium alloys are significantly better than other metals and alloys in both tension and compression. At temperatures of 300–700°F., titanium alloys become markedly superior to aluminum and magnesium alloys. Thus, an application field of tremendous significance exists in structures operating at intermediate temperatures where weight is an important consideration. This is shown by the comparative data in Figure 4.

Titanium exhibits unusual *creep behavior*. Normal time-deformation curves are obtained which show a relatively rapid initial rate of deformation which decreases to a minimum constant value during second stage creep. The minimum creep rate curve fails to follow yield strength, however, and at intermediate temperatures, stresses considerably above the yield strength must be imposed in order to produce appreciable creep. On the other hand, near room temperature and above 700°F. appreciable

TABLE VII. Mechanical Properties of Commercially Pure Titanium.

Commercial designation[a]	Form	Condition	Nominal tensile strength, p.s.i.	Nominal yield strength, p.s.i.	Nominal av. elongation, % in 2 in.	Reduction of area, %	Bend radius, thickness	Nominal hardness[b]
A-55	Sheet	Annealed	65,000	55,000	20	55	1.5–20	RA50–54
	Forgings	Annealed			15	30		RA50–54
A-70	Sheet	Annealed	80,000	70,000	15	50	2.0–2.5	RA54–58
		½ hard	120,000	105,000	12	35		
MST Grade III	Sheet	Annealed	80,000	72,000	25	55		RA60
		Cold-worked (50% reduction)	125,000	110,000	12	30		RA64
	Forgings as forged		80,000	72,000	25	55		RA62
MST Grade IV	Sheet (0.040)	Annealed	100,000	85,000	18	15		RA61
		Cold-worked (37% reduction)	130,000	120,000	6	14		RA65
	Forgings as forged (80% reduction)		80,000	75,000	18	50		RA61
Ti-55A	Sheet and strip	Annealed	55–75,000	35–60,000	26.5	—	1.5	RB75–80
Ti-75A	Sheet and strip	Annealed	75–100,000	60–90,000	21	—	2.3	RB85–95
	Plate	Annealed	70–100,000	55–80,000	21.5	—	2.3	190–240 BHN
	Wire	Annealed	75–90,000	65–80,000	20–25	45–50		
		Cold-drawn (full-hard)	140–150,000	120–130,000	8–15	35–40		
	Hot-rolled bars	Annealed						
	Forgings		70–90,000	50–70,000	20–30	—		160–230 BHN
Ti-100A	Sheet and strip	Annealed	100–120,000	80–110,000	15–20	—	2.6	95RB–25RB
	Plate	Annealed	100–120,000	85–115,000	15–22	—	3.4	250–290 BHN
	Wire	Annealed	100–115,000	80–95,000	20–25	45–50		
		Cold-drawn (full-hard)	185–195,000	155–165,000	10–15	20–30		
	Forgings							
	Hot-rolled bars	Annealed	102,000	88,000	15–25	—		230–270 BHN
RS-40	Sheet forgings	Annealed	50,000	40,000	20	—		RB90
RS-55	Sheet forgings	Annealed	60,000	55,000	20	—		RB95
RS-70	Sheet forgings	Annealed	80,000	70,000	18	—		RB102

[a] A or C, Rem-Cru Titanium, Inc.; RS, Republic Steel Corp.; MST, Mallory-Sharon Titanium Corp.; Ti, Titanium Metals Corp.
[b] RA, Rockwell A; RB, Rockwell B; BHN, Brinell.

creep is observed at stresses below the yield strength. This behavior is in marked contrast to the other structural metals.

TABLE VIII. Mechanical Properties of Titanium Alloys.

Commercial designation[a]	Form	Condition	Nominal tensile strength, p.s.i.	Nominal yield strength, p.s.i.	Nominal av. elongation, % in 2 in.	Bend radius, thickness	Nominal hardness[b]
A-110AT	Sheet	Annealed	120,000	115,000	14	3–4	—
C-110M	Sheet	Annealed	140,000	130,000	12	1.5–3	RC33–36
C-130AM	Bar	Annealed	140,000	130,000	10	—	RC33–36
	Forgings	Annealed	140,000	130,000	10	—	RC33–36
MST 2Al-2 Fe	0.040 sheet	Annealed	140,000	—	14	—	RA68
		Cold-worked 37% reduction	180,000	—	6	—	RA70
	Forgings	Hot-forged 80% reduction	145,000	135,000	12	—	RA68
MST 2.5 Fe-2.5V	0.040 sheet	Annealed	135,000	125,000	10	—	RA65
		Cold-worked 37% reduction	175,000	170,000	2	—	RA68
	Forgings	Hot-forged 80% reduction	130,000	105,000	12	—	RA65
Superior Tube Co.	Tubing	Annealed	85,000 max.	45–60,000	25–34	—	RB90 max.
		Half-hard	85–100,000	65–80,000	6–15	—	RB80–95
		Hard	100–125,000	80–100,000	3–8	—	RB90–RC25
RS-110	—	Annealed	120,000 min.	110,000 min.	12 min.	—	RC35
RS-120	—	Annealed	130,000 min.	120,000 min.	10 min.	—	RC39
Ti-150A	Plate	Annealed	140–165,000	120,000 min.	12 min.	—	311–364 BHN
	Forgings and bars	Annealed	140–160,000	120,000 min.	15 min.	—	311–364 BHN
Ti-175A	Plate	Annealed	165–180,000	140,000 min.	8 min.	—	364–400 BHN
	Forgings and bars	Annealed	160–180,000	140,000 min.	10 min.	—	364–400 BHN

[a] A or C, Rem-Cru Titanium, Inc.; RS, Republic Steel Corp.; MST, Mallory-Sharon Titanium Corp.; Ti, Titanium Metals Corp.
[b] RA, Rockwell A; RB, Rockwell B; RC, Rockwell C; BHN, Brinell.

Commercially pure and alloyed titanium have good *fatigue characteristics* in both the smooth and notched condition. The ratio of notched to smooth endurance limits indicates no unusual notch sensitivity. Resistance to corrosion fatigue in salt water is outstanding and commercially pure titanium is superior to alloys now used in such service.

The *hardness* value for titanium is easy to obtain but difficult to evaluate. This property is affected by many known and apparently several unknown factors which

TABLE IX. Nominal Physical Properties of Titanium Alloys.

Commercial designation[a]	Density, lb./cu.in.	Melting range, °F.	Thermal conductivity B.t.u./(ft.²)(hr.)(°F./in.)	Coefficient of expansion, °F.	Electrical conductivity, % IACS[b]	Modulus of elasticity, p.s.i.
Comm. pure grades	0.163	3135	105	5.0×10^{-6}	3.1	15×10^6
C-110M	0.17	2550-2740	—	—	—	15.5×10^6
C-130AM	0.17	2910-3090	—	—	—	15.5×10^6
MST 2Al-2 Fe	0.165	—	—	5.4×10^{-6}	1.5	17×10^6
MST 2.5 Fe-2.5V	0.167	—	—	5.1×10^{-6}	2.2	15×10^6
MST 3Al-5Cr	0.166	—	—	5.0×10^{-6}	1.2	17×10^6
Ti-150A	0.166	—	92-118	5.0×10^{-6}	3.0	16×10^6
Ti-150B	—	—	92-118	5.0×10^{-6}	—	16×10^6
Ti-175A	—	—	92-118	5.0×10^{-6}	3.0	16×10^6
Superior Tube Co.	0.163	—	110	5.0×10^{-6}	—	$13.0\text{–}19.0 \times 10^6$

[a] A or C, Rem-Cru Titanium, Inc.; RS, Republic Steel Corp.; MST, Mallory-Sharon Titanium Corp.; Ti, Titanium Metals Corp.
[b] International annealed copper standard.

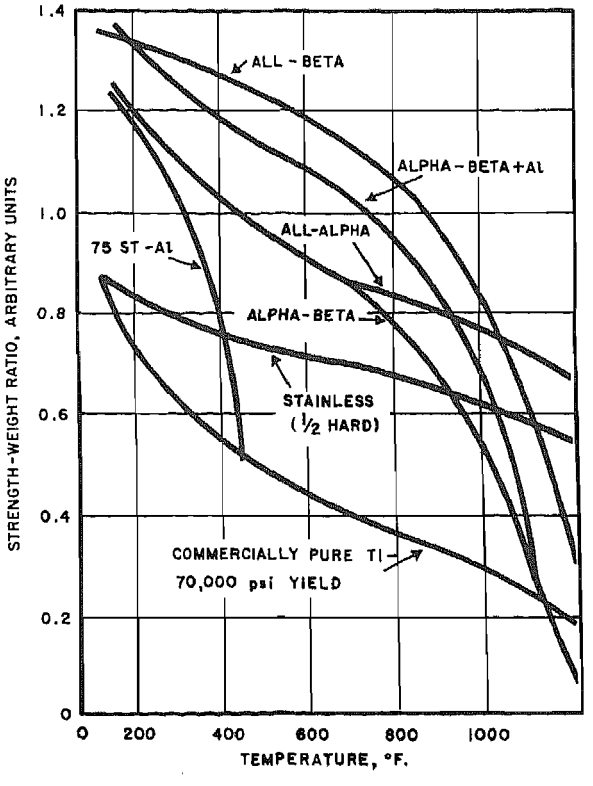


Fig. 4. Strength-weight ratio of titanium-base alloys, 75ST aluminum, and stainless steel.

are insignificant in other metals. For this reason, no reliable correlation between hardness and other physical properties exists at the present time.

Commercial Designations and Alloy Compositions. It has been proposed that

titanium metal products, both commercially pure and alloys, shall be designated by a prefix letter A, B, or C for alpha, beta, or combination-type alloys (see p. 206) (the B alloys are not commercially important, as of 1954), followed by two or three digits representing the yield strength in thousands of pounds per square inch. In the case of alloys, these digits are followed by letters designating the alloy agents. Such designations are used by Rem-Cru Titanium, Inc. Thus, C-130-AM refers to combination alpha-beta alloy, containing aluminum and manganese, having a yield strength of 130,000 p.s.i.

Nominal compositions of some typical commercial titanium alloys, in terms of elements added to commercially pure titanium are shown below. (A or C, Rem-Cru Titanium, Inc.; RS, Republic Steel Corp.; MST, Mallory-Sharon Titanium Corp.; Ti, Titanium Metals Corp.)

Commercial designation	Alloying element, %	Commercial designation	Alloying element, %
RS-110A	7 Mn	MST 3Al-5Cr	3 Al, 5 Cr
RS-120	7 Mn	A-110AT	5 Al, 2.5 Sn
C-110M	8 Mn	Ti-150A	2.7 Cr, 1.5 Fe
C-130-AM	4 Al, 4 Mn	RS-110	3.5 Cr, 1.5 Fe
RS-130	4 Al, 4 Mn	RS-140X	5 Al, 2.75 Cr, 1.25 Fe

CORROSION RESISTANCE

Considerable information is available on the corrosion resistance of unalloyed or commercially pure titanium. Alloys have been available for a limited period of time and comparable data have not been developed. The mechanism which gives titanium excellent corrosion resistance is believed to be the formation and maintenance of a tightly adhering oxide film. Stable films are formed in oxidizing systems, so that mediums otherwise corrosive are frequently tolerated since they may contain oxidizing impurities.

Titanium polarizes rapidly and as a result there is only limited current flow in galvanic and corrosion cells. This not only contributes to the metal's resistance but in the combination of titanium and dissimilar metals there is usually no harmful galvanic effect. In general, titanium corrodes uniformly and there is little or no evidence of pitting or other mechanism involving localized attack. It is not usually subject to stress corrosion, erosion, corrosion fatigue, or intergranular corrosion.

Resistance to Inorganic Chemicals. Commercially pure titanium has excellent corrosion resistance to cold and hot chloride solutions, including cupric and ferric chloride, and also to sodium and calcium hypochlorite. No evidence of stress corrosion has been found in boiling solutions of inorganic chlorides, whereas the common structural metals usually fail in such service.

Chlorine gas containing over 0.013% water has almost no effect on titanium, although the metal will ignite under some conditions in dry chlorine atmospheres.

Chromic acid (CrO_3 dissolved in water) has little effect on titanium although the metal is attacked by sulfuric and hydrochloric acids. It cannot be used in solutions containing over 3% hydrochloric acid unless oxidizing agents, such as nitric acid, are present. The metal is rapidly attacked by hot or concentrated solutions of hydrochloric acid. Similar behavior is exhibited in sulfuric acid, although anodizing greatly improved its resistance.

Although the metal is corroded by all concentrations of hydrofluoric acid, it is

quite resistant to nitric acid, even at elevated temperature and pressure. For example, there was no measurable loss after six months' exposure to 95% acid at 20–25 °C. In addition, very low rates are obtained in red and white fuming nitric acid, although care must be exercised in the use of titanium in such applications. Stress corrosion occurs in red fuming nitric acid and explosive reactions may occur if the metal is highly stressed or cold worked. Special care should be exercised with manganese alloys.

Titanium is fairly resistant to boiling solutions of phosphoric acid up to 5% and at room temperature up to 25%. Ammonium hydroxide (20%) at room temperature and boiling (10%) caustic show no evidence of attack. No appreciable corrosion was found in aqueous hydrogen sulfide, sulfur dioxide, or in molten sulfur.

Resistance to Organic Chemicals and Food Products. Commercially pure titanium is unusually resistant to organic compounds; the only known exceptions are hot solutions of oxalic and trichloroacetic acids and boiling formic acid. Acetic acid in concentrations from 5 to 99.5% at temperatures of 100 °C. has no significant effect on titanium. Similar results are obtained in chloroacetic and dichloroacetic acids; however, titanium dissolves rapidly in trichloroacetic acid. Titanium is also rapidly attacked by all concentrations of hot oxalic acid and boiling nonaerated formic acid. To illustrate the important effect of oxygen, titanium is completely resistant to boiling formic acid if oxidizing agents are present.

In addition to acetic, citric, lactic, and stearic acids, titanium appears to have excellent resistance to other food products. For example, tests of several days' duration showed no attack by coffee, tea, lard, vinegar, and the juice of onion, pineapple, and grapefruit.

Good resistance has been demonstrated in aniline hydrochloride, formaldehyde, carbon tetrachloride, chloroform, ethylene dichloride, tetrachloroethylene, and tetrachloroethane.

Resistance to Natural Environments. Titanium was exposed to the action of sea water for approximately five years under all test conditions available at the International Nickel Company, Kure Beach and Harbor Island test stations. No significant attack was observed in any of these exposures.

The metal is resistant to pitting and crevice corrosion in sea water which are common sources of failure with other materials. Fouling with marine growth occurs but living or dead organisms do not cause localized attack. Titanium also has excellent resistance to the erosive effects of high-velocity sea water. After 60 days rotation at 30 feet per second, cast iron dissolved while titanium was unattacked. In sea water, as in other mediums, titanium quickly polarizes to the potential of more anodic materials to which it is coupled. For example, when joined to 18-8 stainless steel there was no adverse effect on the corrosion rate of the steel specimen although other relatively noble metals resulted in accelerated corrosion.

Metallographic Alloy Types

Titanium transforms from a hexagonal crystal structure to body-centered cubic at 880 °C., and increasing amounts of the common alloying elements progressively raise or lower the transformation point. For example, large additions of chromium allow the body-centered cubic structure to exist below room temperature while aluminum raises the temperature at which the hexagonal phase is stable. Thus the metallurgist

has three basic alloy types: alpha (hexagonal), beta (body-centered cubic), and mixed alpha-beta. This is illustrated in the greatly simplified phase diagram of Figure 5.

Alpha-stabilizing elements include tin, aluminum, boron, carbon, oxygen, and nitrogen. These alloys undergo peritectoid reaction at high concentrations. Almost all of the remaining metals are beta stabilizers. Molybdenum, tantalum, niobium, and vanadium have very similar beta isomorphous diagrams; manganese, chromium, and iron all exhibit a eutectoid reaction.

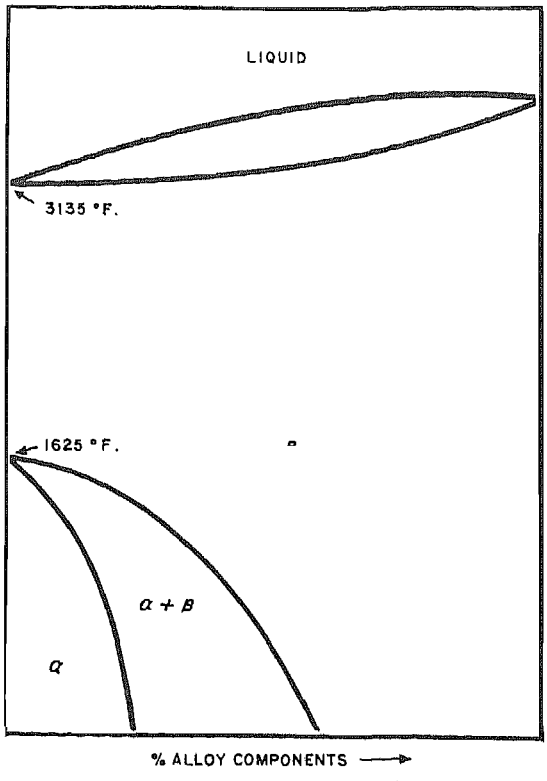


Fig. 5. Generalized alloy phase diagram.

Each of the various alloy categories have certain general characteristics which are tabulated below. There are important differences in temperature dependency between the various titanium alloys depending largely upon their basic crystal structure. (See Table X.)

Titanium in the hexagonal structure differs from magnesium, cadmium, and zinc in that it exhibits more versatile plastic deformation. Slip in these more common hexagonal metals is generally limited to the densely packed basal planes, whereas titanium, having a lower axial ratio, is believed to slip on the prismatic and pyramidal planes as well as the basal plane.

The body-centered-cubic beta structure is, of course, even more versatile in deformation since four slip systems exist. For example, at any given strength level the bend ductilities of beta alloys are always superior to alpha counterparts. Higher temperatures are thus required in working alpha alloys.

In the alpha-beta alloys the properties range between the extremes of the crystal

TABLE X. Comparison of Metallographic Types of Titanium Alloys.

All-alpha Alloys

Advantages

1. Useful strength to almost 1200°F.
2. Resistance to air contamination to 2000°F., thereby permitting higher forging temperature.
3. No embrittling heat-treatment response.
4. Good weldability.

Disadvantages

1. Sheet bend ductility not as good as that of alpha-beta alloys; considerably poorer than that of beta alloys.
2. Requires more power for hot working than alpha-beta.

Alpha-Beta Alloys

Advantages

1. Double the strength of unalloyed titanium.
2. Good ductility, including bend.
3. Forging, rolling, and forming easier than alpha and than beta (beta has better bend ductility)
4. Relatively simple to produce in quantity.
5. Heat treatable to higher strengths.

Disadvantages

1. Heat treatment response (if not controlled results in loss of ductility).
2. Poorer weld ductility than alpha.
3. Temperature ceiling for useful strength about 800°F.

Unstable Beta-Rich Alloys

Advantages

1. Quenchable to give medium strength with high ductility.
2. Can be heat treated to higher strength (with some loss in ductility) after fabrication.
3. Elevated temperature properties similar to alpha-beta alloys.

Disadvantages

1. Embrittled by 24–96 hours at 350–800°F.
2. Control of composition critical.
3. Restricted to parts that can be heat-treated after fabrication or parts that require little forming after heat treating.

Stable Beta-Rich Alloys

Advantages

1. Excellent ductility in all forms (0.020 sheet will bend flat on itself).
2. High strength useful to approximately 1000°F.
3. Does not require heat treatment for high strength.
4. No heat treatment response.

Disadvantages

1. Very sensitive to contamination during production.
2. Sensitive to air contamination above 1300°F.
3. High strength means greater springback in forming.
4. Relatively high content of strategic alloying materials.

systems. The determining factor is the relative quantity of alpha to beta phase present. In an alpha-strengthened two-phase system, bend ductility is poor, whereas in a beta-strengthened alloy, bend ductility is always excellent. On the other hand, alpha-strengthened systems have superior high temperature properties.

The microstructure of titanium is principally influenced by the allotropic transformation at 880°C. from the hexagonal to the body-centered-cubic crystal form. Worked and annealed commercially pure titanium has an equiaxed grain structure.

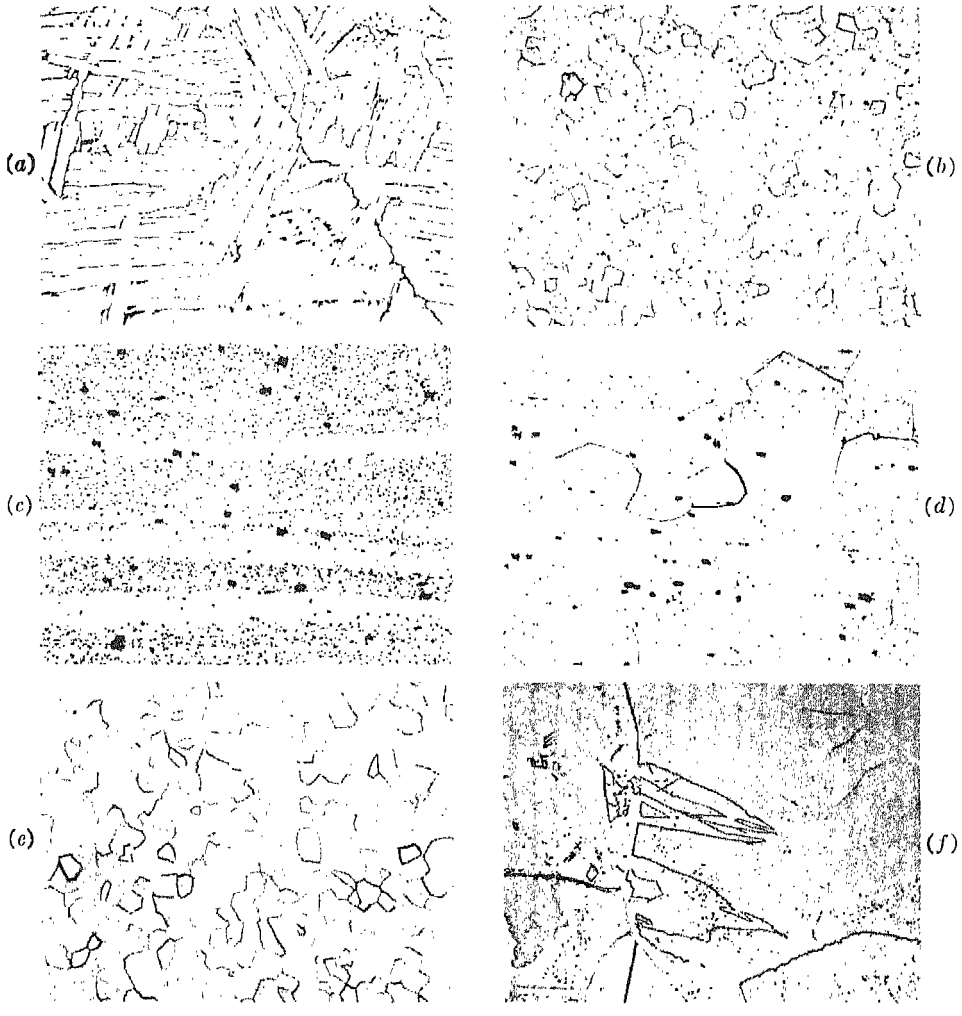


Fig. 6. Typical microstructures of titanium alloys (×100). (*a*) Forged commercial-purity-grade titanium. Coarse acicular alpha titanium structure formed by forging in the beta temperature range. (*b*) Unalloyed titanium metal, rolled and annealed at 1400°F. Equiaxed alpha structure. (*c*) Alpha-beta titanium alloy (8% Mn). Alpha particles in beta matrix, plus dispersed carbides. Water-quenched from 1500°F. Beta banding apparent from chemical inhomogeneity. (*d*) Alpha-beta type titanium alloy (8% Mn), retained beta plus dispersed carbides. Water-quenched from 1650°F. (*e*) Alpha titanium alloy (5% Al), rolled and annealed at 1600°F. Equiaxed alpha structure. (*f*) Weld structure in 1/16-in. titanium sheet produced from high-purity sponge. Coarse alpha titanium cast structure. Slight weld porosity apparent.

Iron can cause small spheroids of retained beta in the microstructure. Hydrogen results in a rodlike precipitate of titanium hydride. Carbon above 0.2% usually appears as gray spheroidal particles of titanium carbide. Quenching from above the transformation point results in an acicular structure which varies with the oxygen and

nitrogen content of the metal. Twinning occurs very easily and frequently obscures the true microstructure. Cold working produces the usual fibered structure with elongated grains. Typical microstructures are shown in Figure 6.

Alpha alloys, including commercially pure metal, cannot be significantly strengthened by heat treatment although the possibility of compound precipitation hardening exists. Beta alloys likewise cannot be usefully heat-treated. Alpha-beta alloys, to the contrary, are very responsive to quench hardening due to retention of varying amounts of unstable high-temperature phases of beta origin, which subsequently transform to alpha.

Sponge titanium metal produced by magnesium reduction of titanium tetrachloride usually contains about 99.5% titanium. Table XI shows the common contaminants in order of decreasing amount.

TABLE XI. Typical Analysis of Commercial Sponge.

Element	Range, wt. %	Nominal level wt. %
Titanium	99.2 –99.8	99.5
Iron	0.1 – 0.50	0.25
Oxygen	0.05 – 0.20	0.10
Chlorine	0.02 – 0.15	0.08
Magnesium	0 01 – 0.10	0.05
Nitrogen	0.005– 0.05	0.03
Carbon	0.01 – 0.05	0.03
Manganese	0.01 – 0.10	0.03
Tin	0.01 – 0.05	0.02
Silicon	0.01 – 0.05	0.01
Aluminum	0.01 – 0.05	0.01
Hydrogen	0.001– 0.10	0.004

Oxygen is a powerful alpha strengthener and has found some limited use as an alloying agent, although it loses strength rapidly at higher temperatures. In general, it is an undesirable contaminant possibly intensifying notch sensitivity, and should be held to as low a level as practical. There is no known method for its removal from titanium, in which it dissolves interstitially without precipitation. The sources of oxygen are raw materials, equipment leaks, water vapor, and atmospheric oxygen. Analytical determination is difficult and vacuum fusion with carbon is the only reliable technique.

Nitrogen is an even more powerful alpha strengthener, but its adverse effect on ductility has prevented even limited use in alloying. Like oxygen, there is no practicable method for its removal. It dissolves interstitially and results primarily from equipment leakage.

Carbon also dissolves interstitially but precipitates as titanium carbide above about 0.2% in alpha-titanium. This element occurs in limited quantities in the raw materials and is quantitatively absorbed by the titanium.

Hydrogen, a beta stabilizer, dissolves interstitially but can be removed by vacuum at elevated temperature. It is undesirable because of its adverse effect on toughness. Alpha alloys cannot tolerate above 50 p.p.m. hydrogen and alpha-beta systems should be held to less than 100 p.p.m.

Magnesium and magnesium chloride remain in small quantities after vacuum distillation. These elements volatilize during melting and their importance is related to

splattering of the molten pool. In permanent electrode furnaces, they must be held to a low level to prevent excessive solution of the carbon or tungsten cathode. Consumable electrode furnaces eliminate this particular problem, although both magnesium and magnesium chloride can contribute to poor wall surface and thence yield loss. Magnesium is by far the most important on a weight per cent basis because of its low molecular weight and low boiling point relative to magnesium chloride.

Manganese, tin, silicon, and aluminum occur in the raw materials and at the indicated nominal level have no known adverse effects.

Health and Safety Precautions

The chemical inertness of titanium and its oxide is well known. Thousands of tons of titanium dioxide pigment have been produced and utilized without evidence of ill effects.

Injection tests of titanium powder have shown only inert body irritation. Ingestion has given no pathological symptoms. Wrought metal actually has been used in bone surgery because of its inertness and the fact that living tissue will attach to it.

Titanium powder, like other metal powders, is highly pyrophoric. Adequate ventilation and lubricants should be provided during sawing, grinding, or polishing. The characteristic intense white spark ending in a fiery burst which occurs when titanium is brought in contact with a grinding wheel has become a means of identification. Massive forms are resistant to ignition and will not burn unless heat is continuously supplied to maintain combustion. Liquid titanium burns in air and fire control is similar to that for magnesium. Dry sand, inert gas, and/or flux may be employed. Water and carbon dioxide may do more harm than good.

Applications

Owing to limited supply the present applications of titanium are almost completely for the military, particularly in jet aircraft. Its use pattern is a function of a unique combination of properties, namely, light weight, high strength, and good corrosion resistance. At intermediate temperatures, titanium offers weight savings over both alloy steel and alloy aluminum.

Manufacturers of both airframes and aircraft power plants predict a growing application for titanium alloys in components exposed to the temperature range of 0–450°C. A few of the items currently under evaluation by the airframe producers are skin, fire walls, landing-gear components, hydraulic tubing, exhaust shrouds, oil and fuel tanks, nacelle structures, fasteners, and engine supports. In gas turbine power plants, compressor disks, compressor blades, compressor housings, retaining rings, and fasteners are being fabricated. As a single example, titanium has found extensive use in North American's F-100, the Super Sabre.

Although only limited data are available, it has been reported that titanium alloy's resistance to ballistic penetration is greater than conventional armor plate of equal weight. This obviously has broad military significance.

Other applications of the favorable strength-weight ratio may be found where power loss through momentum is involved. Reciprocating equipment, steam turbines, gas turbines, textile machinery, and diesel engines are potential fields of application.

The excellent corrosion resistance of titanium can be applied in the chemical and

allied industries. In many cases full-scale equipment tests are under way on autoclaves, heat exchangers, agitators, and lined tanks. Complex organic acid solutions encountered in food processing require very resistant materials and titanium has shown promise. Inertness toward sulfur, sulfur compounds, and saline solutions indicates a place in the petroleum industry.

At a low price its marine applications would be unlimited. Future applications are forecast in heat exchangers, propellers, shafting, deck hardware, underwater mufflers, and all types of pumps, valves, and metering devices.

The growing military demand for titanium has prevented evaluation of the civilian market although a few applications have developed. Titanium's tendency to polarize rapidly in 15% sulfuric acid and fluoboric acid has led to its evaluation as a rack material in anodizing aluminum. Douglas Aircraft was the first to use the metal in a commercial airliner. The DC-7 superliner utilizes titanium in the engine nacelles and fire walls. This very limited substitution for aluminum and stainless steel will result in a weight savings of about 200. lb. per plane.

It must be emphasized that the potential of titanium can be realized only when it is designed into the initial unit. In aircraft, for example, substitution of titanium for stainless steel saves less than ½ lb. per pound used. If, on the other hand, titanium is designed originally into the plane, savings in wing surface, fuel, power, etc., can easily result in an overall effect of 5 lb. per pound of application.

There are two additional fields that do not involve its use as a material of construction. The growing demand for purer alloying agents in ferrous and nonferrous alloys had led to its use as a substitute for ferrotitanium and related master alloys. Here chemical purity is the major factor and there is some evidence that alloys prepared with high-purity titanium are cleaner and freer from impurities than those prepared with more conventional addition agents. The second nonstructural application is in pyrophoric firing mixtures for various ordnance items. The high stability of titanium powder in moist air is the basis of this use.

The future of titanium is unalterably tied to its selling price. Major reductions in the selling price of sponge and mill products are essential to establishment of a tonnage civilian market. At a base price for mill products of \$3–5 per pound, a market of 10,000–20,000 annual tons has been forecast; at \$1.50 per pound titanium may approximate the current consumption of stainless steel. Present prices (1954) for mill products range from \$10 to \$20 per pound. Reductions have been made in the selling price of both sponge and mill products and a gradual downward trend is predicted. Considering that the metal was first offered for commercial sale in late 1948, progress has been astounding.

Bibliography

(1) Ashburn, A., "How to Work Titanium and Its Alloys," *American Machinist*, **95**, 145–53 (June 11, 1951).

(1a) Barbsdale, J., *Titanium, Its Occurrence, Chemistry, and Technology*, Ronald Press, N.Y., 1949.

(2) Cockrell, W. L., "Titanium Takes the Test," *Finish*, **9**, No. 6, 19–21 (1952).

(3) Dean, R. S., and Silkes, B., "Metallic Titanium and its Alloys," U.S. Bur. Mines, *Inform. Circ.*, **7381** (1946).

(4) DeHuff, P. G., and Hazelton, W. S., "Titanium at Work in Jet Engines," *Westinghouse Eng.*, **12**, 118–20 (1952).

(5) Dickinson, T. A., "Some Hints on Fabricating Titanium," *Steel Processing*, **38**, 333–34, 339 (July 1952).

(6) Eshman, A. N., "Titanium Sheetmetal Parts Successfully Made," *Iron Age*, **170**, No. 3, 132–35 (1952).
(7) "Fabrication of Titanium," *Light Metal Age*, **9**, 14–15 (April 1951).
(8) Finlay, W. L., and Vordahl, M. B., "Titanium Alloys Today," *Metal Progress*, **61**, 73–78 (Feb. 1952).
(9) Gee, E. A., Golden, L. B., and Lusby, W. E., Jr., "Titanium and Zirconium Corrosion Studies," *Ind. Eng. Chem.*, **41**, 1668–73 (1949).
(10) Gee, E. A., Sutton, J. B., and Barth, W. J., "Effect of Carbon in Titanium Metal Ingots," *Ind. Eng. Chem.*, **42**, 243–49 (1950).
(11) Gee, E. A., and Waggaman, W. H., "Metallic Titanium Is Light, Strong, Durable and Corrosion-Resistant," *Materials and Methods*, **27**, 75 78 (January 1948).
(11a) Gmelin, 8th ed., 1900, System-Nummer 41.
(12) "Grinding Methods Evolved for Titanium," *J. Metals*, **3**, 1128–29 (1951).
(13) "Grinding Titanium-Wheels and Techniques," *Norton Tech. Bull.*, No. **512A**, (October 1951).
(14) Goldberg, D. C., and Hazelton, W. S., "How to Machine Titanium," *Iron Age*, **169**, No. 16, 107–10 (1952).
(15) *Handbook on Titanium Metal*, 5th ed., Titanium Metals Corp. of America, N.Y., 1952.
(16) Hutchinson, G. E., and Permar, P. H., "Corrosion Resistance of Commercially Pure Titanium," *Corrosion*, **5**, 319–25 (1949).
(17) Jaffee, R. I., Ogden, H. R., and Maykuth, D. J., "Alloys of Titanium with Carbon, Oxygen, and Nitrogen," *J. Metals*, **188**, 1261 (1950).
(18) Johnson, J. B., and Hassell, E. J., "Titanium in Aircraft," *Metal Progress*, **60**, No. 3, 51–55 (1951).
(19) Joseph, J., "Titanium Fabrication Progress," *Light-Metal Age*, **10**, 10–11, 30 (February 1952).
(20) *Liquid-Metals Handbook*; NAVEXOS P-733, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., June 1, 1950.
(21) Maha, E. M., and Hitchcock, R. B., "Effect of Welding on Properties of Titanium-Carbon Alloys," *Welding J.*, **29**, 544s–51s (1950).
(22) McElgin, J., "Experience Growing in Forming, Machining Titanium Alloys," *Steel*, **129**, No. 14, 68–69 (1951).
(23) Ochler, I. A., "Titanium Alloys Flash Welded Easily," *Steel*, **131**, No. 2, 84–85 (1952).
(24) "Our Next Major Metal—Titanium" (Special Progress Report), *Product Engineering*, **20**, 129–52 (November 1949).
(25) Radtke, S. F., Scriver, R. M., and Snyder, J. A., "Arc Melting of Titanium Metal," *J. Metals*, **191**, 620–24 (1951).
(26) *Rem-Cru Titanium Manual* (Vol. 2, No. 6), Rem-Cru Titanium, Inc., Midland, Pa., January 1954.
(27) *Rem-Cru Titanium Review*, Rem-Cru Titanium, Inc. (Vol. 1, No. 1, June 1952).
(28) *Rem-Cru Titanium and Titanium Alloys*, Rem-Cru Titanium, Inc., Midland, Pa., rev. July 1952.
(29) *Republic Titanium and Titanium Alloys*, Republic Steel Corp., Massillon, Ohio, 1954.
(30) *Resistance and Fusion Welding of Titanium and its Alloys* (Tech. Inform. Bull.), Mallory-Sharon Titanium Corp., Niles, Ohio.
(31) Rosenberg, A. J., and Hutchinson, E. F., "How to Weld Titanium," *Am. Machinist*, **96**, 93–97 (May 26, 1952).
(32) *Some Notes on the Physical Metallurgy of RC-130A and RC-130B Alloys*, Rem-Cru Titanium, Inc., Midland, Pa.
(33) "Stainless Fabricating Methods Successfully Form Titanium Sheet," *Steel*, **129**, No. 24, 94–95, 110 (1951).
(34) Stevenson, F. H., "Tips on Welding High-Temperature Materials," *Iron Age*, **168**, No. 3, 109–10 (1951).
(35) Straumanis, M. E., and Chen, P. C., "The Corrosion of Titanium in Acids," *Corrosion*, **7**, 229–37 (1951).
(36) Sutton, J. B., Gee, E. A., and DeLong, W. B., "Casting and Forging of Titanium," *Metal Progress*, **58**, 716–20, 720B (1950).
(37) Thompson, J. M., *Anal. Chem.*, **24**, 1632–34 (1952).
(38) "Titanium and Its Alloys," *Materials and Methods*, **35**, 117–32 (May 1952).

(39) "Titanium—How it Fits in Your Tomorrow," *Steel*, **128**, No. 2, 54–59, 79–80, 82 (1951).
(40) "Titanium Machines Like Jet-Engine Alloys," *Steel*, **129**, No. 17, 74–77 (1951).
(41) "Titanium Tests Tools, Talent," *Am. Machinist*, **96**, 91–96 (April 28, 1952).
(42) *Titanium Tubing* (Data Sheet) Bull. **42**, Superior Tube Co., Norristown, Pa.
(43) *U.S. Bur. Mines, Rept. Invest.*, **4153** (December 1947); **4519** (August 1949).
(44) "Welding Study—Titanium and Titanium Alloy Sheet," *Am. Machinist*, **96**, 98–99 (May 26, 1952).
(45) Wheelon, O. A., "Design and Manufacturing Techniques with Titanium," Paper presented before SAE National Aeronautic Meeting, Los Angeles, California, October 3–6, 1951.
(46) Williams, W. Lee, "The Titanium Program at the U.S. Naval Experiment Station," *J. Am. Soc. Naval Eng.*, **62**, 855–69 (1950).
(47) Van Arkel, A. E., and de Boer, J. H., *Z. anorg. u. allgem. Chem.*, **148**, 345–50 (1925).
(48) U.S. Pat. 2,205,854 (June 25, 1940), W. F. Kroll.

C. H. WINTER, JR., AND E. A. GEE

TITANIUM COMPOUNDS

Inorganic Compounds..... p. 213
Organic Compounds..... 237

INORGANIC TITANIUM COMPOUNDS

From its position in group IVa of the periodic table, titanium might be expected to exhibit a valence number of +4 (titanic) in most of its compounds. However, it also forms stable compounds in which it has valence numbers of +3 (titanous) and +2, and stable solutions of peroxy type compounds (see Vol. **10**, p. 49). This behavior is typical of the transition elements of which group titanium is a member. The grouping TiO in compounds such as $TiOSO_4$ is usually called titanyl, but the existence of a TiO^{2+} ion is doubtful.

One of the most characteristic properties of quadrivalent titanium compounds is the ability of their acid and aqueous solutions to undergo hydrolysis to yield hydrous titanium oxide. By adjustment of acidity, concentration, and other factors, hydrolysis may be readily controlled to produce hydrolyzates of desirable physical properties. This controlled hydrolysis from titanium – iron sulfate solution, prepared by treating ilmenite ore with sulfuric acid, forms the basis of the titanium dioxide pigment industry.

Another characteristic of titanium compounds, which is also shared by other multivalent elements, is the ability of intermediate valence stages to disproportionate into higher- and lower-valent forms. Reduced titanium halides have been prepared by this procedure, and it has been suggested as a method for preparing titanium metal.

The two most common starting materials for preparing inorganic titanium compounds are titanium tetrachloride and titanium sulfate. Titanium tetrachloride is produced in quantity by chlorinating ilmenite or rutile ores, whereas titanium sulfate is obtained by treating hydrous titanium oxide with concentrated sulfuric acid. Titanium sulfate solution containing iron and other impurities is an important intermediate in the industrial production of titanium dioxide pigments from ilmenite. Large quantities of this solution are available for producing inorganic titanium compounds.

Bibliographies and detailed information on titanium and its compounds are

given by Barksdale (1), Gmelin (12), Du Mont (7), and Skinner, Johnston, and Beckett (25).

Titanium Borides.

Titanium monoboride, TiB, formula weight 58.72, is prepared by heating equimolar amounts of titanium and boron powders. It has a face-centered cubic structure of the NaCl-type, where a_0 = 4.26 A. Its electrical resistivity is 40 microhm-cm. An orthorhombic form of the FeB-type, unit cell dimensions a_0 = 6.12, b_0 = 3.06 and c_0 = 4.56 A, is also reported.

Titanium diboride, TiB_2, formula weight 69.54, is a gray, crystalline solid. The structure is simple hexagonal of the AlB_2-type. Cell dimensions are a_0 = 3.028 and c_0 = 3.228 A, corresponding to a theoretical density of 4.52 g./cu.cm. The compound melts at approximately 2790°C., and has a Vicker's hardness of 3400 kg./sq.mm. (100 g. load). Its electrical resistivity is 15.5 microhm-cm. at room temperature. It is not visibly attacked by cold, concentrated hydrochloric or sulfuric acids, but dissolves slowly at boiling temperatures. It is rapidly dissolved by hot, concentrated nitric acid and aqua regia. The diboride can be made by treating titanium metal powder with boron powder in a vacuum or by treating titanium hydride with boron powder in the atmosphere of the liberated hydrogen. It is used with metal binders for high-temperature applications where high-temperature strength and resistance to oxidation are necessary. Because of its hardness, it is a potential substitute for diamond dust in cutting and grinding applications.

A tetragonal dititanium monoboride, Ti_2B, and a hexagonal dititanium pentaboride, Ti_2B_5, have been reported (24).

Titanium Carbide.

Titanium carbide, TiC, formula weight 59.91, is a gray, metallic solid with a face-centered cubic structure of the NaCl-type. It has a lattice constant of 4.329 A., which corresponds to a theoretical density of 4.90 g./cu.cm. The compound melts at 3250°C., and has a Vicker's hardness of 3200 kg./sq.mm. (100 g. load). Its electrical resistivity is 70 microhm-cm. at room temperature. It shows no apparent reaction with cold, concentrated hydrochloric or sulfuric acid, but is slowly dissolved on heating. It is readily attacked by hot, concentrated nitric acid and aqua regia.

Titanium carbide can be prepared by reducing titanium dioxide with carbon at high temperatures in a vacuum or protective atmosphere; also by the reaction of titanium with carbon in a molten metal solution such as iron or nickel. Its principal use is as a hard component for cutting tools and for applications where high-temperature strength is needed.

Titanium Carbonitride.

A titanium carbonitride having the composition Ti_5CN_4 has been prepared by the reduction of titanium dioxide with carbon in the presence of nitrogen. The composition of the carbonitride can be varied depending upon the composition of the titanium dioxide – carbon mixture, the nitriding gas employed, and the temperature used. The carbonitride is used principally as a source material for the preparation of titanium tetrachloride by direct chlorination.

Titanium Halides.

Titanium dichloride, $TiCl_2$, formula weight 118.82, forms black, hexagonal crystals having a density of 3.13. It does not sublime on heating in vacuum to temperatures as high as 600°C., but above this temperature it gradually decomposes to titanium metal and titanium tetrachloride. It oxidizes rapidly in moist air to titanium dioxide and hydrogen chloride and reacts with water, liberating hydrogen and forming a solution of titanium trichloride. Titanium dichloride may be prepared by the disproportionation of titanium trichloride at about 475°C. in a vacuum. Where titanium metal is available, it may be prepared conveniently by treating the metal with titanium tetrachloride at about 900°C.

Titanium trichloride (titanous chloride), $TiCl_3$, formula weight 154.28, forms dark purple, hexagonal crystals, sp.gr. 2.66. It may be sublimed at about 425°C. in vacuum but at higher temperatures it decomposes to titanium tetrachloride and titanium dichloride, which remains behind as a residue. In moist air, it is oxidized rapidly to titanium dioxide and hydrogen chloride, but in water, purple solutions are formed, which are stable when kept in an oxygen-free atmosphere. Titanium trichloride may be prepared readily by the reduction of titanium tetrachloride with hydrogen at elevated temperatures. The trichloride is formed on a cooled tube projecting into the reaction mixture. Titanium, or the alkali or alkaline earth metals may also be used for reducing agents.

Titanium trichloride hexahydrate, $TiCl_3.6H_2O$, may be crystallized from aqueous titanium trichloride solution and has been of some commercial interest as a reducing agent. There is no commercial interest in the anhydrous product. The hexahydrate has the advantage over the anhydrous salt in being prepared rather easily on a large scale. Thus, aqueous titanium tetrachloride solutions may be reduced electrolytically until practically all of the titanium is in the trivalent state, the solution concentrated by evaporation, and the hexahydrate crystals separated from the mother liquor by filtration or centrifuging.

Titanium tetrachloride, $TiCl_4$, formula weight 189.73, is a clear, colorless liquid, f.p. −24.8°C., b.p. 135.8°C., d^{25} 1.719. It dissolves in water to form clear solutions that are hydrolyzed readily to yield a series of basic chlorides, $Ti(OH)Cl_3$, $Ti(OH)_2Cl_2$, $Ti(OH)_3Cl$, and finally hydrous titanium oxide, $TiO_2.xH_2O$. It is readily reduced by hydrogen, alkali metals, or alkaline earth metals to lower chlorides, and in some cases to the free metal. It forms addition compounds with ammonia, hydrogen sulfide, phosphorus trichloride, hydrogen cyanide, and various organic compounds. It also reacts with certain organic compounds, for example with alcohols to form titanium esters.

Titanium tetrachloride is prepared commercially by the chlorination of mixtures of carbon and titanium dioxide or by the chlorination of titanium carbonitride. The raw material for the titanium dioxide chlorination feed may be a rutile ore of high titanium dioxide content, while the carbonitride may be derived from technical-grade titanium dioxide, which itself has been produced from ilmenite ore. The crude titanium tetrachloride obtained by chlorination must be purified further by treatment and distillation, particularly to remove small amounts of impurities such as vanadium tetrachloride and ferric chloride.

Titanium tetrachloride is the most important titanium halide. Its chief use is as a starting material in the commercial production of titanium metal, but small amounts

are also used for producing smoke screens and for skywriting. It has been used as a starting material for titanium dioxide pigments prepared both by hydrolysis from aqueous solution and by vapor-phase oxidation, but these methods are of little significance compared to the commercial method of production from titanium sulfate solution. Small quantities of titanium tetrachloride are also used in producing rutile gem stones and titanium organic compounds.

Chlorotitanates (hexachlorotitanates(IV)), M_2TiCl_6, of cesium and rubidium are known.

Titanium dibromide, $TiBr_2$, formula weight 207.74, is a deep black powder, sp.gr. 4.31. It does not sublime at 400°C., but it begins to decompose into titanium metal and titanium tetrabromide at about 500°C. In air it oxidizes rapidly and in water it liberates hydrogen. Titanium dibromide may be prepared by the careful addition of bromine to titanium metal or by the disproportionation of titanium tribromide at 400°C.

Titanium tribromide, $TiBr_3$, formula weight 287.66, is a blue-black crystalline powder which occurs in two crystallographic forms: hexagonal and a form which is either hexagonal, tetragonal, or orthorhombic. At temperatures below about 400°C. titanium tribromide may be sublimed, but above this temperature, it decomposes into titanium tetrabromide and titanium dibromide. It oxidizes rapidly in air to titanium dioxide, but forms stable dark-violet aqueous solutions.

As with titanium trichloride, the tribromide also may be prepared by hydrogen reduction of titanium tetrabromide using a cold tube to freeze out the product. Other reducing agents such as titanium or the alkali metals or alkaline earth metals also may be used.

Titanium tribromide hexahydrate, $TiBr_3.6H_2O$, may be obtained as reddish-violet crystals from aqueous titanium tribromide solution by evaporating and cooling. It is most easily prepared by reducing tetrabromide solutions electrolytically until all of the titanium is in the trivalent state and then proceeding as above.

Titanium tetrabromide, $TiBr_4$, formula weight 367.56, is a lemon-yellow, deliquescent, crystalline powder. It belongs to the cubic system; m.p. 38.2°C., b.p. 230°C., sp.gr. 3.25. It reacts with cold water, forming solutions containing titanium oxybromide and hydrobromic acid, but readily undergoes hydrolysis in hot solutions to form hydrous titanium oxide. Basic salts corresponding to the formulas $Ti(OH)_2Br_2$ and $Ti(OH)_3Br$ have been reported. As with titanium tetrachloride it may be reduced to lower halides by hydrogen or metals of the alkali or alkaline earth groups. Addition compounds are also formed with ammonia, hydrogen sulfide, phosphorus trichloride, hydrogen cyanide, and certain organic compounds.

Titanium tetrabromide may be prepared by the bromination of titanium carbonitride or titanium dioxide – carbon mixtures. It also may be prepared by treating titanium tetrachloride with hydrogen bromide and gradually increasing the temperature until titanium tetrabromide is distilled out. This salt has been used as a starting material for producing titanium metal, but appears to be of little commercial importance at present.

Titanium diiodide, TiI_2, formula weight 301.72, crystallizes as black, shining platelets. It appears to be dimorphous, but only the crystal structure of the hexagonal modification has been determined. Its density is 4.3. It does not sublime in vacuum at temperatures as high as 450°C., but at higher temperatures it both sublimes and decomposes to titanium metal and titanium tetraiodide. In air it is very

hygroscopic and oxidizes rapidly, while it reacts strongly with water to produce hydrogen.

Titanium diiodide is prepared by reacting titanium metal with iodine and heating the mixture to 440°C. to remove the tri- and tetraiodides. It also may be prepared by reducing titanium tetraiodide with silver or mercury. Except for its occurrence as an intermediate in the preparation of very pure titanium metal, titanium diiodide is not of commercial importance.

Titanium triiodide, TiI_3, formula weight 428.63, forms violet-black, needle-like crystals with a metallic sheen. It does not sublime when heated in vacuum to 300°C., but at about 350°C. it begins to decompose into titanium diiodide and titanium tetraiodide. It dissolves in water to form stable solutions. Titanium triiodide may be prepared by direct reaction of the elements under carefully controlled conditions. The hexahydrate may be prepared by electrolytically reducing an aqueous solution of titanium tetraiodide, evaporating, cooling, and separating the resultant crystals. It oxidizes rapidly in air.

Titanium tetraiodide, TiI_4, formula weight 555.54, forms reddish-brown, octahedral crystals in the cubic system, m.p. 150°C., b.p. 377°C., sp.gr. 4.40. It fumes in air and is converted rapidly to titanium dioxide. It dissolves in water to form solutions that are readily hydrolyzed to basic salts and finally to hydrous titanium oxide and hydriodic acid. Addition compounds are formed with a few organic compounds.

Titanium tetraiodide may be prepared by treating titanium metal with iodine under carefully controlled conditions. It also may be prepared by treating liquid titanium tetrachloride with hydrogen iodide and gradually increasing the mixture temperature until titanium tetraiodide is distilled out. It has no commercial importance as a chemical product but is an important intermediate in the preparation of very pure titanium metal from crude metal.

Titanium difluoride, TiF_2, formula weight 85.90, dark purple, prismatic crystals, is said to have been prepared by heating potassium fluotitanate in hydrogen. Its existence has not been established with certainty.

Titanium trifluoride, TiF_3, formula weight 104.90, forms deep purple crystals which are soluble in water. It may be prepared by reducing the tetrafluoride with alkali metals or alkaline earth metals.

Titanium tetrafluoride, TiF_4, formula weight 123.90, is a white hygroscopic powder, sp.gr. 2.798. When heated it sublimes. Its boiling point has been calculated to be 284°C. It is soluble in water, from which a dihydrate may be obtained by evaporation. The most convenient method of preparation is by treating liquid titanium tetrachloride with anhydrous, liquid hydrogen fluoride. Hydrogen chloride is evolved and, upon distilling the mixture, titanium tetrafluoride is obtained as a high-boiling fraction.

Potassium fluotitanate (potassium hexafluotitanate(IV)), K_2TiF_6, formula weight 240.10, forms small, highly reflecting, rhombohedral crystals; m.p. 780°C., sp.gr. 3.012. On heating in air above 500°C., it is gradually oxidized to titanium dioxide and potassium fluoride. It is moderately soluble in hot water and, upon cooling, the monohydrate, $K_2TiF_6.H_2O$, crystallizes out.

Potassium fluotitanate may be prepared by dissolving titanium dioxide in hydrofluoric acid, adding potassium fluoride, cooling, crystallizing, and filtering to obtain the monohydrate. This may be easily dehydrated by heating above 100°C. Potassium fluotitanate is used as a grain-refining agent for aluminum, as a gelling agent

for rubber, and has been suggested as a starting material for the preparation of titanium metal by fused salt electrolysis.

Titanium Hydrides.

Titanium hydride is a metallic-appearing powder of variable chemical composition. It exhibits two solid-solution phases of hydrogen in titanium, an α-phase poor in hydrogen and a β-phase rich in hydrogen. The existence range of each phase depends on pressure and temperature. In general the α-phase is stable at higher temperatures over a wide pressure range, whereas the β-phase is stable at lower temperatures and high pressures. Both phases may coexist over a limited pressure-temperature range (12,16,17). X-ray diffraction studies of titanium hydride preparations have shown that the α-phase is hexagonal and the β-phase face-centered cubic. There is some evidence that well-defined compounds such as TiH_2 and TiH_4 exist, particularly the former, but these have not been well substantiated (9,10).

Small amounts of hydrogen dissolved in titanium metal do not change its density appreciably. However, a composition corresponding to $TiH_{1.62}$ has a density of 3.91 which is considerably less than that of pure titanium metal (density 4.52). Hydrogen absorption in titanium metal is a reversible phenomenon; low temperatures and high pressures favor the absorption of large amounts of hydrogen. Substantially all of the hydrogen may be removed from titanium hydride by heating in vacuum at 600°C. (14). In air, titanium hydride is not hygroscopic and is stable, but when heated to 800°C. it burns with a great evolution of heat.

Titanium hydride may be prepared by heating titanium metal powder with hydrogen. The composition depends on the pressure and temperature. It may also be prepared by treating titanium dioxide with calcium hydride or titanium tetrachloride with sodium hydride. It has found some application in the welding industry, as a flux for the preparation of ceramic or glass-to-metal seals, and for introducing titanium metal into alloys where a protective atmosphere is necessary. Its use has been proposed for titanizing copper, nickel and iron plates to impart a hard coating of a titanium-copper alloy. Iron and nickel are coated with copper before titanizing.

Titanium Nitrate.

Titanium nitrate is probably formed by dissolving hydrous titanium oxide or titanates in nitric acid. On evaporation, a plate-like basic salt, $5TiO_2.N_2O_5.6H_2O$, is formed.

Titanium Nitrides.

Titanium mononitride, TiN, formula weight 61.91, is a bronze-yellow solid. Its crystal structure is face-centered cubic, NaCl-type. The lattice constant is 4.235 A., corresponding to a theoretical density of 5.43 g./cu.cm. It melts at 2950°C., and has an electrical resistivity of 21.7 microhm-cm. at room temperature. A Knoop hardness of 1770 kg./sq.mm. (100 g. load) has been reported. Its molal entropy at 298.16°K. is 7.20 e.u./mole. The material is not readily attacked by hydrochloric, nitric, or sulfuric acid, but is dissolved by aqua regia. Titanium mononitride can be prepared by roasting titanium metal with pure nitrogen. It has no important uses at present.

Other titanium nitrides corresponding to the compositions Ti_3N_4, Ti_3N_6, and Ti_5N_6 have been reported.

Titanium Oxides.

Titanium monoxide, TiO, formula weight 63.90, is a light-bronze solid. It has a face-centered cubic structure, NaCl-type, and a lattice constant of 4.176 A. which corresponds to a theoretical density of 5.8 g./cu.cm. It melts at 1760°C., and has a Vickers hardness (5 kg. load) of approximately 1300 kg./sq.mm. The electrical resistivity is 300 microhm-cm. at 20°C. Titanium monoxide is slowly attacked by hot, concentrated hydrochloric, sulfuric, and nitric acids; it is dissolved by hot, concentrated hydrofluoric acid. Titanium monoxide can be prepared by roasting titanium metal with titanium dioxide (5,8).

Titanium sesquioxide, Ti_2O_3, formula weight 143.80, is a dark-violet solid. The compound is hexagonal, corundum-type, with lattice constants of $a_0 = 5.14$ and $c_0 = 13.61$ A. A pycnometer density of 4.48 g./cu.cm. and a melting point of 1900°C. have been reported. Titanium sesquioxide is only slightly attacked by hot, concentrated sulfuric acid, but is readily dissolved by hot, concentrated hydrofluoric acid. It can be prepared by roasting titanium metal with titanium dioxide. It has no important uses at present.

Trititanium pentoxide (titanium tritapentoxide, anosovite), Ti_3O_5, formula weight 223.70, is a bluish-black solid having a metallic luster. The compound crystallizes in the orthorhombic system, with unit cell constants of $a_0 = 3.747$, $b_0 = 9.465$, and $c_0 = 9.715$ A., which give a calculated density of 4.29 g./cu.cm. The melting point of a composition close to Ti_3O_5 has been reported as 1857°C. It can be prepared by roasting titanium metal with titanium dioxide or by reduction of titanium dioxide with hydrogen or carbon monoxide at 700–1100°C. It has no important uses at present.

The specific heats of TiO, Ti_2O_3, and Ti_3O_5 have been measured between 52 and 298°K. and the molal entropies computed to be 8.31, 18.83, and 30.92 e.u./mole, respectively. The heat contents above 298.16°K. have been measured, and the specific heat equations developed. These three oxides exhibit transition points at 1224 ± 10°, 473 ± 20°, and about 450°K., respectively.

Titanium Dioxides, Hydrous Titanium Oxides, and Titanates. Titanium dioxide (titania), TiO_2, formula weight 79.90, exists in three forms: anatase (octahedrite), brookite, and rutile. *Anatase* is tetragonal, uniaxial negative, $\epsilon = 2.493$, $\omega = 2.554$; the unit cell contains four TiO_2 molecules and has a volume of 136.1 A^3. *Rutile*, tetragonal, is isomeric but not isomorphous with anatase; uniaxial positive, $\epsilon = 2.903$, $\omega = 2.616$; the unit cell has two TiO_2 units and a volume of 62.4 A^3. *Brookite* is orthorhombic, biaxial positive, $2V = 30°$ for sodium light, 0° for yellow green, dispersion very strong, $n_\alpha = 2.583$, $n_\beta = 2.586$, $n_\gamma = 2.741$. Figure 1 shows the crystal unit cells of anatase and rutile. Anatase and rutile can best be distinguished by x-ray diffraction methods; x-ray data are recorded in reference (26). X-ray spectrometric tracings showing the intensity of diffraction for anatase and rutile at different angles are given in reference (28).

Anatase and brookite are apparently monotropic forms and can be changed to the stable rutile at a rate which increases with the temperature. For the natural minerals in the absence of mineralizers, Schroeder (23a) found that brookite was changed to rutile above 650°C., while anatase inverted to rutile at 915 ± 15°. However, in the presence of suitable fluxes Bunting (5a) found that anatase and brookite converted to rutile at much lower temperatures (400–500°C.) than those reported by

Schroeder. Artificially prepared anatase products are known that convert to rutile as low as 100–300°C. (20).

While the three crystal forms of titanium dioxide are found in nature, only anatase and rutile are produced commercially. Formation of the particular crystal species is controlled in the manufacturing process.

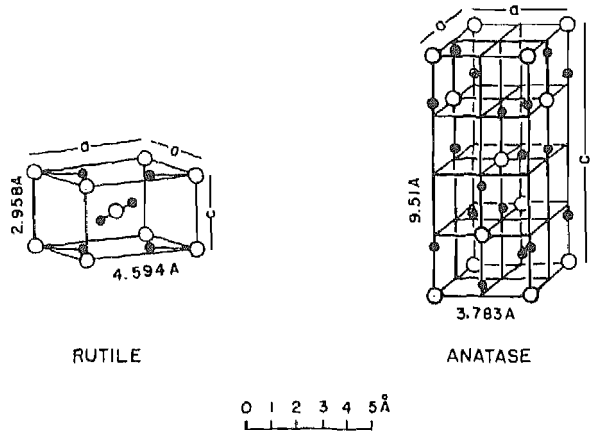


Fig. 1. Crystal unit cells of anatase and rutile.

Anatase and rutile are characterized by high indexes of refraction, which account for their high opacity and hiding power relative to other white pigments. Furthermore, titanium dioxide is extremely stable at ordinary temperatures. It is relatively insoluble in water, organic acids, dilute alkalies, and in most inorganic acids. Only hot concentrated sulfuric or hydrofluoric acid will dissolve titanium dioxide. It is unaffected by gases, particularly those found in the atmosphere, but under certain conditions and in the presence of organic matter, it is converted to lower oxides. The reduced oxides are also formed by treating titanium dioxide with reducing gases (hydrogen, carbon monoxide, etc. at moderately high temperatures (600–900°C.)). Titanium dioxide reacts with carbon and nitrogen at elevated temperatures to form carbides, nitrides, and carbonitrides. It also reacts with other metal oxides to form so-called titanates (see p. 231).

Some physical properties of titanium dioxide are shown in Table I.

TABLE I. Some Physical Properties of Titanium Dioxide.

Property	Anatase	Rutile	Brookite
Crystal system	Tetragonal	Tetragonal	Orthorhombic
M.p., °C.	—	1825	—
Sp.gr.	3.90	4.27	4.13
n_D	2.52	2.72	2.63
Mohs' hardness	5.5–6.0	7.0–7.5	5.5–6.0
Specific heat, cal./(°C.)(g.) at 298°K.	0.169	0.169	—
Mean dielectric constant	48	114	78[a]
Electrical conductivity, in air, mho/cm.			
At room temperature	—	10^{-13}–10^{-14}	—
At 500°C.	5.5×10^{-5}	—	—
At 1200°C.	—	0.12	—

[a] Direction of *a* axis.

Hydrous titanium oxides are amorphous masses, as shown by x-ray analysis, having the empirical formula $TiO_2.xH_2O$, where x, the number of molecules of bound water, varies over wide limits depending on the method of preparation. Although this formula represents hydrous titanium oxide as a hydrated oxide, another system of nomenclature is in common use which classifies the hydrous oxides as either ortho- or metatitanic acids. The term orthotitanic acid is used to designate those hydrous titanium oxides that are highly hydrated and energy-rich, and contain two or more moles of water per mole of titanium dioxide. The term metatitanic acid is reserved for those hydrates that are less energy-rich and contain approximately one mole of water per mole of titanium dioxide (1,12).

Orthotitanic acid may be prepared by the direct addition of alkali to titanium chloride or titanyl sulfate solution. The resultant precipitate may be removed by filtration, washed, and dried. Other titanium salt solutions may also be used as starting materials, but are not so readily available as the chloride and sulfate.

Metatitanic acid may be readily prepared by heating dilute, aqueous solutions of titanium tetrachloride or titanyl sulfate. The metatitanic acid is precipitated as a gelatinous material which may be separated by filtration from the hydrolysis liquor, washed, and dried.

Hydrous titanium oxide is soluble in concentrated sulfuric acid or hydrofluoric acid, but is not appreciably soluble in other inorganic acids. It may, however, be readily peptized by monobasic acids provided that it is sufficiently free of entrapped salts or polyvalent ions (sulfates) from the hydrolysis liquor. It is not soluble in alkalies but does undergo changes in hydration and other physical properties when thus treated.

For **inorganic titanates** see p. 231; for **organic titanates** see p. 238.

Manufacture of Titanium Dioxide

Titanium dioxide pigments are produced as titanium dioxide or as composites in combination with either 70 or 50% calcium sulfate and are used extensively in paints, paper, plastics, rubber, ceramics, porcelain enamels, and other applications. The distribution of titanium pigment shipments in 1953 for consumption in industry (18) showed that 58.8% (titanium dioxide content) was used in paints, varnishes, and lacquers; 14.1% in paper; 5.4% in floor covering; 4.5% in rubber; 2.6% in coated fabrics and textiles; 1.6% in printing inks; and 13.0% in other industries. (See *Paint*; *Pigments*.) Titanium dioxide also has nonpigmentary uses (see p. 230).

SOURCE MATERIALS

The most important titanium ores are naturally occurring rutile (TiO_2) and ilmenite. Ilmenite deposits are found as black beach sands and in massive rock formations usually associated with hematite or magnetite. These ores are classed as ilmenite-hematites and titaniferous magnetite. Other less important ores are sphene (calcium titanium silicate) and perovskite (calcium titanate). In addition, titanium is often found in fairly large quantities in bauxite and may be recovered as a by-product in the production of alumina (11).

Rutile deposits of commercial importance are found in Florida, Quebec, Norway, and Australia. The ore, after suitable beneficiation to remove siliceous material, zircon, etc., analyzes about 94–96% TiO_2, the balance being chiefly iron oxide.

TABLE II. Analysis of Ilmenites.

Component	MacIntyre, New York	Norwegian	Quilon, India	Malayan	Yadkin Valley, North Carolina	Canadian slag
TiO_2, %	44.6	43.5	59.9	51.9	50.6	72.1
FeO, %	36.7	32.6	9.3	38.8	33.2	8.9
Fe_2O_3, %	8.2	13.8	25.2	5.3	7.3	None
Fe, %	—	—	—	—	—	0.21
Fe, total, %	34.4	35.0	24.8	33.9	30.9	8.2
SiO_2, %	4.0	4.0	0.7	0.4	2.7	5.8
Al_2O_3, %	3.2	1.3	1.6	1.5	3.3	6.5
P_2O_5, %	0.04	0.03	0.18	0.2	0.15	0.01
MgO, %	2.6	3.9	0.95	0.08	3.3	5.9
CaO, %	0.8	0.6	<0.1	0.1	2.8	1.4
Nb_2O_5, %	0.01	0.01	0.17	0.22	0.12	<0.01
MnO, %	0.32	0.40	0.48	0.8	0.52	0.26
Cr_2O_3, %	0.015	0.015	0.13	0.015	0.28	0.24
V_2O_5, %	0.12	0.23	0.25	0.03	0.30	0.54
$FeO:Fe_2O_3$ ratio	4.5	4.2	0.37	7.3	4.5	—

Ilmenite sands are found in Java, Australia, New Zealand, Senegal, Malaya, Ceylon, Brazil, and India. The deposits in India have been the most important, and from them a large proportion of the ilmenite supplies of the world were produced before World War II.

Ilmenite-hematite ore is found in large massive deposits in the Allard Lake region in Canada. The hematite occurs as veinlets oriented along crystallographic planes in the ilmenite.

Titaniferous magnetites are found in the U.S. in New York, Arkansas, North Carolina, Virginia, Wyoming, and Minnesota. Large deposits are also found in Norway, Canada, Madagascar, Australia, and the U.S.S.R. The ores contain about 20% TiO_2 and the titanium is present as grains, inclusions, or intergrowths of the ilmenite in the magnetite, or as an integral part of the magnetite. Beneficiation of the ore to remove the magnetic fraction results in products analyzing from 40 to 50% TiO_2.

Ilmenite is variable in chemical composition. It is often referred to as a ferrous titanate, $FeO.TiO_2$, but it seldom corresponds to this formula because the iron is always present in both ferrous and ferric states. Its composition varies according to its

TABLE III. Consumption of Ilmenite and Rutile in the U.S. 1944–1953, in Short Tons.

	Ilmenite				Rutile for all uses	
	For pigments[a]		For other uses[b]			
Year	Gross weight	Estimated TiO_2 content	Gross weight	Estimated TiO_2 content	Gross weight	Estimated TiO_2 content
1944	349,505	170,518	11,434	4,957	14,813	13,837
1946	399,042	200,352	5,241	2,311	7,134	6,670
1948	558,448	297,728	6,552	2,680	9,863	9,144
1950	671,335	347,747	7,909	3,928	11,721	10,869
1951	703,068	367,937	10,295	5,100	17,227	16,018
1952	670,829	345,368	12,021	6,185	18,317	17,353
1953	684,707	353,354	10,837	5,486	20,170	19,033

[a] "Pigments" includes all manufactured TiO_2.
[b] Other uses are welding-rod coatings, alloys, and carbides, ceramics, and miscellaneous.

origin and it is frequently found associated with excess ferric oxide or excess titanium oxide. Typical analyses of various types of ilmenite are shown in Table II. Australian ore (not listed) is characterized by high chromium and aluminum values (20).

In addition to these ores, **slags** containing 60–75% TiO_2 became available in 1951. The slags are prepared by electrothermal smelting of Canadian ilmenite-hematite with coal and limited additions of lime to produce a pig iron product and a titanium slag concentrate containing about 65–70% TiO_2 which is separated from the iron while in the molten state. The analysis of a Canadian slag is included with the data shown in Table II.

The consumption of ilmenite and rutile in the U.S. for the period 1944 to 1953 is shown in Table III (19). Consumption of titanium slag was as follows:

Year	Gross weight, short tons	Estimated TiO_2 content
1952	24,236	16,746
1953	73,528	52,511

PROCESSES OF MANUFACTURE (1,22,27,28)

Methods for the production of titanium dioxide from its ores fall into three groups: (*1*) thermal hydrolysis of titanium sulfate, chloride, or nitrate solutions, (*2*) neutralization of titanium fluoride solution with ammonia, and (*3*) reaction of titanium tetrachloride vapor with an oxygen-containing gas at elevated temperatures (vapor-phase oxidation reaction).

Of these, the *thermal hydrolysis* of titanium sulfate solutions, commonly known as the *sulfate process*, is the best known and most widely used. Titanium chloride and nitrate solutions have received little attention because of the corrosiveness of the solutions and higher operating costs.

In the *fluoride process*, ilmenite ore is treated with ammonium fluoride or bifluoride, NH_4HF_2. The reaction mass is extracted with water and the solution of titanium and ammonium fluorides, containing also a small amount of iron fluoride as impurity, is filtered to remove the practically insoluble double fluoride of iron and ammonia. The solution is neutralized with ammonia (pH about 6.8) and sulfided to remove the iron. The iron-free solution is treated with an excess of ammonia to precipitate the titania as hydrous oxide, which is then filtered, washed, and calcined. Recovery of the fluorine and ammonia are essential for economic operation. The fluoride process has not been commercially successful in view of the processing difficulties encountered in handling the corrosive solutions and in the recovery of the reactants (6,36).

Considerable interest is manifest in the United States and in Europe in the *vapor-phase oxidation* of titanium tetrachloride, judging from the number of patents which have been issued since about 1949 on this process. Titanium tetrachloride vapor and an oxygen-containing gas are treated at elevated temperatures with the formation of a flame. In some instances, an auxiliary flame produced by the combustion of carbon monoxide or a hydrocarbon gas and an oxygen-containing gas is employed.

For example, pigmentary titanium oxide is reportedly produced by passing preheated titanium tetrachloride vapor and an oxygen-containing gas into the inner annular spacings of a multiple-tube burner and burning the mixture in contact with an auxiliary flame obtained by flowing an auxiliary combustible gas and an auxiliary

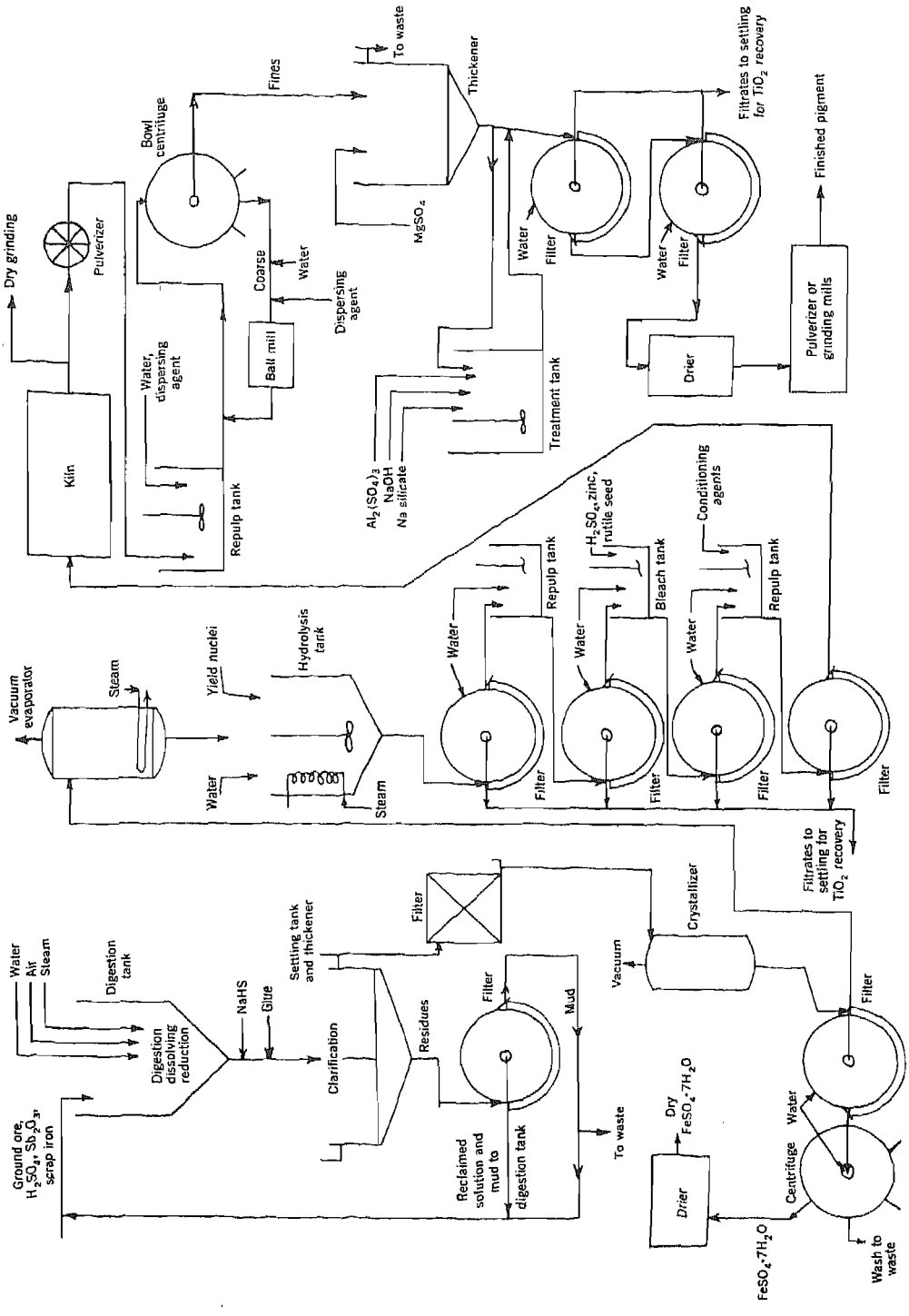


Fig. 2. Flow sheet for manufacture of titanium oxide pigments.

oxidizing gas through the outer annular spacings of the burner (44). In another flame-combustion process, the vaporized halide and air are introduced into an annular blanket of flame derived from the combustion of a hydrocarbon gas and an excess of oxygen. Sufficient hydrocarbon is present to ensure, upon combustion of the hydrocarbon, hydrolysis of all the hydrolysable halide (47). In a third modification, an auxiliary flame is not employed. Instead preheated titanium tetrachloride and an oxygen-containing gas suitably humidified with 0.1–5% (based on the total volume of gases) of water vapor are introduced separately and continuously into a specially designed reactor while a shielding inert gas film is maintained over the internal surfaces of the reactor. In this manner contact of the reactants with the surface of the reactor is prevented and deposition or build-up of objectionable oxide scale on the surface is avoided. The shielding gas is introduced into the reaction zone through a porous refractory wall. The addition of aluminum chloride with the titanium tetrachloride is reported to impart desirable characteristics to the titanium oxide product (43,45).

In view of the expanding production of titanium tetrachloride for use in the manufacture of titanium metal, it is very likely that the vapor-phase oxidation reaction will receive increasingly more attention in the future.

Manufacture of titanium dioxide by the *sulfate process* involves the following six important operations: (*1*) digestion and dissolving of the ore; (*2*) clarification of the solution; (*3*) hydrolysis to precipitate hydrous titanium oxide; (*4*) filtration and washing of the hydrous oxide; (*5*) calcination; and (*6*) finishing treatment and grinding of the pigment.

A flow sheet for the production of anatase and rutile titanium dioxide pigments is shown in Figure 2.

Digestion. Ilmenite ore is digested with sulfuric acid to convert the iron and titanium components of the ore to soluble iron and titanium sulfates. If the composition of ilmenite is represented by the formula $FeO(Fe_2O_3)TiO_2$, the reaction with sulfuric acid can be written as follows with the formation of ferrous sulfate, ferric sulfate, and titanyl sulfate:

$$FeO(Fe_2O_3)TiO_2 + 5\,H_2SO_4 \longrightarrow FeSO_4 + Fe_2(SO_4)_3 + TiOSO_4 + 5\,H_2O$$

An excess of acid over that required to convert all the titanium and iron to the corresponding sulfates is usually employed.

There are two known types of digestion: (*1*) the continuous method which was used in England and on the Continent, but has since been discontinued, and (*2*) the batch method which is employed by all major producers of titanium oxide pigments.

Continuous Method (38). A pug mill with two helicoidal screw conveyors acting in parallel at different speeds is employed for carrying out the digestion reaction. Pulverized ilmenite and oleum in predetermined proportions are continuously added to an agitated premix tank and the mixture is allowed to flow into the feed end of a screw conveyor. Simultaneously with this acid-ore mixture, water or dilute acid is fed into the conveyer. Immediately heat is developed and the exothermic reaction between the acid and ore begins. As the reaction proceeds, the mass gradually thickens and is moved forward by the helicoidal screws. The temperature of the mass is controlled by varying the rotation of the paddle shafts and by varying the amount of diluent added to the oleum-ore mixture. Best results are obtained by operating

under such conditions that the mass is allowed to become dry in the first half of the conveyer length. The cake discharging from the reactor is leached with water or dilute sulfuric acid. Conversion of the titanium in the ore to a soluble sulfate is in the order of 90–95%.

Batch Method (34). The ilmenite ore, which is received either as a beneficiated sand or as rock disintegrated to the size of sand, is dried in a continuous, direct-fired rotary kiln to less than 0.5% moisture. The dried ore is then fed to a ring-roll mill, such as a Raymond type mill, or to a continuous steel-lined ball mill, where it is ground to a fine powder (95% through a 200-mesh screen) and thence conveyed to a storage bin.

Strong sulfuric acid (66°Bé.) is measured into a large cone-bottom digestion tank and agitated with air. The ground ilmenite ore and a small quantity of antimony trioxide are added to the acid over a period of 15–30 minutes, air agitation being continued during the period. A typical batch formulation is 50,000 lb. of 66°Bé. sulfuric acid, 40,000 lb. of ilmenite ore, and 175 lb. of antimony oxide.

The mixture is heated with direct steam to about 110–120°C., and sufficient water (175 gal.) is added to dilute the concentration of the acid to 90%. The reaction that occurs is exothermic and under certain conditions can become very violent. The mixture passes through a pasty stage and is finally converted to a comparatively solid dry mass, honeycombed in structure as a result of air agitation during the reaction. Water or a dilute acid solution is added and the cake is dissolved under carefully controlled conditions of temperature and concentration. The solution of titanium and iron sulfates thus obtained is treated with scrap iron (4000 lb.) to reduce the ferric iron to the ferrous state. To assure the absence of ferric iron in subsequent processing of the solution, a small portion of the titanium in solution is also reduced to the trivalent state. At this stage of the operation, the solution contains about 120–130 g./l. TiO_2 and 250–300 g./l. $FeSO_4$.

Clarification. In addition to the dissolved titanium and iron, the solution contains some unreacted ilmenite as well as siliceous matter which remains in suspension. These solid materials are removed from the solution by the addition of coagulating agents and subsequent settling. The coagulating agents generally consist of a soluble sulfide such as sodium hydrosulfide and a proteinaceous material such as glue, which form a floc of antimony sulfides and carry down the suspended colloidal silica, etc. The clarified liquor is decanted. The mud residue is pumped out of the bottom of the settling tank and filtered to recover the titanium sulfate solution which is returned to the dissolving system. In some instances, the mud residue filter cake is recycled to the digestion tank and redigested with fresh ilmenite to recover the titanium and antimony values.

The clarified solution is then pumped to a vacuum crystallizer and cooled to about 10°C. to crystallize out a large proportion of the iron as copperas, $FeSO_4.7H_2O$. The mixture is filtered to remove the copperas crystals, and the crystals are given a light wash to remove and recover any adhering titanium solution. The solution thus obtained is subjected to a second clarification operation to remove the last traces of residue. The liquor is treated with a diatomaceous earth filter aid and filtered. A rubber-covered steel filter press or filter tubes of porous carborundum are used for this operation. The solution at this stage contains: 140–150 g./l. TiO_2, 120–150 g./l. $FeSO_4$, and 280–330 g./l. H_2SO_4. The filtered solution is concentrated under reduced pressure in a continuous lead evaporator to approximately 200–250 g./l. TiO_2, the level of con-

centration depending to some degree upon the specific hydrolysis method subsequently employed to precipitate the titanium oxide.

Hydrolysis. In hydrolysis, the soluble titanyl sulfate is converted to an insoluble hydrous titanium oxide. The hydrolysis step is one of the most critical operations in the manufacturing process and conditions must be controlled carefully to insure the precipitation of a product of suitable particle size, maximum yield, and freedom from occluded impurities, particularly iron salts. These objectives are realized by (*1*) strict control of the concentration of the solution and the ratio of sulfuric acid to titanium dioxide in the solution, (*2*) the temperature and rate of application of heat to the solution, (*3*) the maintenance of a small concentration of titanous sulfate in the solution during the hydrolysis to prevent oxidation of the ferrous sulfate, and (*4*) the addition to, or formation of, nuclei in the solution to accelerate and control the rate of hydrolysis.

Use of Nuclei. The early practice in hydrolysis was to control the concentration of titanium oxide and sulfuric acid in solution very closely and to boil the solution until a satisfactory yield of titanium oxide was obtained. However, this procedure did not give uniform results and the products were extremely variable in particle size. Various hypotheses were advanced to explain these effects, the most plausible of which was based upon the assumption that "auto-nucleation" of the solution occurred both before and during the boiling period. This nucleation, which is difficult to control, determines the number of centers of growth in the solution and, to some extent, the type of hydrous oxide formed.

In present-day practice, nucleation of the ilmenite sulfate solution is very carefully controlled. Two general nucleation methods are employed which are characterized as (*1*) Blumenfeld type, in which the nuclei are developed *in situ*, and (*2*) Mecklenburg type, in which the nuclei are separately prepared and added to the solution to be hydrolyzed.

In the Blumenfeld type of nucleation, a specified volume of hot titanium sulfate solution under controlled conditions of concentration and temperature is run at a controlled rate into a specified volume of hot water with agitation (33). A precipitate of hydrous titanium oxide is formed which redissolves with continued addition of the hot sulfate solution. Subsequent boiling of the mixture results in rapid hydrolysis of the titanyl sulfate. For example, 4000 gal. of an ilmenite sulfate solution containing 250 g./l. TiO_2, 200 g./l. $FeSO_4$, 550 g./l. H_2SO_4, and 3 g./l. TiO_2 in the titanous form are heated to 96°C. in a suitable tank. Simultaneously, 1000 gal. of water are heated to 91°C. in a separate tank having sufficient capacity to hold the entire volume of both liquids. The ilmenite solution is then added to the water with agitation at a rate of 250 gal. per minute. The temperature of the resulting mixture is raised to the boiling point at the rate of ⅓ of a degree per minute and boiling is continued until a 95% recovery of the titanium values is obtained (usually from 3 to 5 hours).

In the Mecklenburg type of nucleation a portion of the ilmenite sulfate solution is partially neutralized with caustic soda or soda ash to precipitate hydrous titanium oxide under controlled pH conditions, and the mixture is heat treated for a specified time and temperature. An ilmenite solution or a relatively iron-free titanyl sulfate solution may be used as a source material for nucleus preparation. Approximately 1% of the seed is used based on the titanium oxide content of the solution to be hydrolyzed (32).

For example, a portion of an ilmenite sulfate solution containing 180–200 g./l. TiO_2 and 400–450 g./l. H_2SO_4 is treated with aqueous sodium hydroxide to a pH of 4 (methyl orange indicator) and the mixture is then heated for about 30 minutes at 75–80°C. The cured suspension is added to the remaining ilmenite solution and the mixture is boiled until a satisfactory recovery of the titanium values is obtained. Many variants of such externally prepared yield seeds are reported. According to one modification, an ilmenite sulfate solution containing 200 g./l. TiO_2 is treated with sodium carbonate to neutralize the titanyl sulfate and the free acid but not the ferrous sulfate. A pH of 4.0 should not be exceeded and the final temperature of the mix is about 60°C. The mass is then agitated, cooled, and dried. For hydrolysis ½–1% seed on the TiO_2 basis of the solution treated is used (39).

Filtration and Washing. The precipitated hydrous titanium oxide is pumped from the hydrolysis tank to a cooling tank and thence to a battery of filters. A precoated leaf or rotary filter is employed in the first stage to remove the bulk of the iron sulfate in solution and a large proportion of the sulfuric acid. The filter cake is washed, then repulped with fresh water, and refiltered. This filtration and washing operation requires considerable care, otherwise the color of the final product can be affected adversely.

The last traces of iron are removed by repulping the filter cake with dilute sulfuric acid, heating the slurry with titanous sulfate or zinc dust to reduce any ferric iron present, and then filtering and washing over a second battery of rotary filters.

Calcination. The washed and repulped filter cake, which still contains a quantity of adsorbed sulfuric acid, is treated with various conditioning agents before calcination in a rotary kiln. The alkali and alkaline earth oxides, carbonates, and phosphates, and antimony trioxide are among the agents added to the pulp before calcination to control particle-size growth and develop the highest hiding power and good color.

During calcination, water and sulfuric acid are driven off; the particle size of the titanium oxide crystallites is increased, and the index of refraction rises from about 1.75 for the hydrous oxide product to about 2.5 for the anatase crystal and 2.7 for the rutile crystal, with a corresponding increase in opacity of the pigment. Calcination also results in aggregation of the particles into small lumps having free-flowing characteristics to facilitate handling and minimize dust losses. The calcination temperature which may be carried as high as 1000°C. is carefully controlled.

The hydrous titanium oxides precipitated from ilmenite sulfate solutions with the aid of Blumenfeld or Mecklenburg type nuclei have the anatase structure. When anatase-grade pigments are desired, subsequent processing operations (calcination and addition of conditioning agents) are controlled to preserve the anatase structure in the finished pigment. To produce rutile-grade pigments, rutile-promoting seeds as well as zinc and magnesium salts may be added to accelerate the conversion of the anatase base to rutile. The rutile-grade pigments have approximately 30% greater hiding power than the corresponding anatase grades.

For the preparation of rutile pigments from sulfate solutions, nuclei of a special type are required to promote the conversion of anatase to rutile during calcination. These special nuclei, called rutile-promoting seeds, are usually derived from a titanium chloride solution or dispersions of orthotitanic acid or alkali metal titanates in hydrochloric acid. They may have either the anatase or the rutile structure and they are characterized by their ability to promote the conversion of anatase hydrous oxides to rutile upon calcining the hydrolyzates at comparatively low temperatures (800–

900°C.). Rutile-promoting seeds may be substituted for or used in conjunction with the Blumenfeld or Mecklenburg type of nuclei at hydrolysis, or they may be incorporated with normal anatase hydrolyzates before calcination. Examples are given below of the preparation of rutile-promoting seeds from (*a*) orthotitanic acid peptized with hydrochloric acid, (*b*) from pure titanium tetrachloride solution, and (*c*) from an alkali metal titanate dispersed in hydrochloric acid.

(*a*) A relatively iron free titanyl sulfate solution is neutralized with sodium carbonate to precipitate pure orthotitanic acid. The precipitate is filtered and washed until substantially free from sulfates. The orthotitanic acid is slurried with water and acidified with hydrochloric acid to yield a suspension in which the ratio of acid to titanium dioxide (HCl/TiO_2) on a weight basis is about 0.4/0.5. The suspension is heated to 85°C., and the seed aged for a period of 30 minutes during which time the titanium oxide is peptized to a colloidal sol. The sol is cooled to room temperature and may be used in this form or it may be coagulated by neutralization with caustic soda solution, and the coagulated seed then filtered and washed free of chloride ions (41).

(*b*) A titanium tetrachloride solution containing about 80–100 g./l. TiO_2 is added with stirring to an equal volume of caustic soda solution containing sufficient alkali to neutralize roughly 75% of the available hydrochloric acid. The resulting mixture is heated to 85°C. and held at this temperature for 30 minutes, after which it is cooled to room temperature. This seed also may be used in this form, or it may be neutralized with alkali and the coagulated seed then filtered and washed free of chloride ions.

(*c*) An aqueous pulp of substantially pure hydrous titanium oxide obtained by hydrolytic precipitation from a titanium sulfate solution and containing 100 g. of titanium dioxide is diluted with water to about 30% calcined solids content. To this slurry is added 150 g. of flake sodium hydroxide while stirring continuously and at a constant volume. The titanate thus formed is filtered and washed substantially free of sulfates. The filter cake is slurried in 185 ml. of commercial 20°Bé. hydrochloric acid, 4 ml. of a titanous chloride solution containing 100 g. titanous chloride per liter is added, and the whole diluted with one liter of water and boiled at constant volume for about one hour. After cooling to room temperature, the seed may be used in this form, or it may be neutralized with alkali, then filtered, and washed free of chlorides (42).

Finishing Treatment and Grinding of the Pigment. The material discharged from the calciner is processed according to the requirements of its end use. In some instances, the calcine is simply dry-ground in a ring-roll mill equipped with air separators. This product has relatively poor wetting and dispersive properties in oleoresinous vehicles. To improve these properties, the calcine is pulverized and slurried with water. This slurry is treated with an alkali silicate or phosphate which acts as a dispersing agent and the mixture is fed to a hydroseparator or a centrifugal classifier where the fines are removed. The coarse gritty particles are returned to a pebble mill where they are reground and recycled to the classification system. The fine material passes to a thickener where it is coagulated by the addition of magnesium sulfate or calcium chloride. The thickened pulp is filtered and washed, after which the filter cake is fed to a continuous dryer. The dried product is then ground either in a ring-roll mill or a simple hammer pulverizer. For certain grades of pigment, the thickened pulp is treated with various hydrous oxides and silicates; for example, those of aluminum, zinc, magnesium, and titanium, to modify the surface of the titanium di-

oxide and to impart specific characteristics to the pigment, such as superior chalk resistance or color retention in particular types of paint films. The treated slurries are then filtered, washed, dried, and ground as above.

CALCIUM-BASE COMPOSITE TITANIUM OXIDE PIGMENTS

These composite pigments are of two types: (*1*) *coalesced* pigments in which a fine-particle-size anhydrite ($CaSO_4$) is suspended in an ilmenite sulfate solution and the hydrous titanium oxide is precipitated on the surface of the anhydrite; these products require calcination at elevated temperatures to develop the particle size and tinctorial strength of the titanium oxide; (*2*) *blended* pigments in which aqueous slurries of anhydrite and "calcined" pigmentary grades of titanium oxide are mixed, after which the mixtures are dewatered and calcined lightly to insure the absence of gypsum in the final product.

Coalesced Pigments (37). A dehydrated calcium sulfate suspension is prepared by adding a slurry of hydrated lime or limestone to concentrated sulfuric acid under controlled conditions of concentration, temperature, and time of heating to produce a very finely divided product having the anhydrite structure. Clarified ilmenite sulfate solution is added to this slurry and the mixture is heated to boiling and maintained at boil until at least 95% of the titanium is hydrolyzed. The composite precipitate is then filtered, washed, dried, calcined, and dry-milled. The quantities of anhydrite and ilmenite sulfate solution are adjusted to produce composite pigments of the desired composition, for example, 30% TiO_2 or 50% TiO_2.

Blended Pigments (35). Anhydrite is prepared by treating hydrated lime with concentrated sulfuric acid under controlled conditions. The product is filtered and washed until it is substantially free of acid (filtrate shows a pH of at least 4). The cake is repulped in fresh water (made alkaline by adding a small amount of sodium hydroxide) and again filtered. Calcium sulfate produced in this manner is either calcined separately and then mechanically mixed with titanium dioxide pigment of specified characteristics, or, for the sake of simplicity and ease of operation, the two components are blended before calcination of the calcium sulfate.

NONPIGMENTARY TITANIUM DIOXIDE

Nonpigmentary titanium dioxide is produced in either a finer or coarser particle size than the pigmentary material. The use of the coarse material for nonpigmentary purposes is preferable for many reasons, chief among these being its ease of handling, freedom from dusting, ease of blending with other materials, and control of its shrinkage when it is fired as a ceramic body.

Large tonnages of the coarse, high-purity titanium dioxide are utilized by porcelain enamel manufacturers. Not only does the material impart acid resistance to enamels but, because of its excellent opacifying properties, the enamel may be applied in thinner coatings, thereby increasing its flexural strength and effecting a cost and weight saving. In the manufacture of a porcelain enamel the titanium dioxide is incorporated into the original batch, generally in amounts of from 10 to 20% by weight. The batch is then smelted until all of the materials are dissolved. Following this, the molten material is quenched in water. The resultant product, known as "frit," is a clear glass which is supersaturated with titanium dioxide. The frit is then suspended in water and ground. The resulting slurry, called a "slip," is then applied to the metal base by dipping or spraying. The coated base object is next heated to melt the pow-

dered glass and fuse it to the metal. During this heating, the titanium dioxide crystallizes from the supersaturated glass, thereby imparting the desired opacity to the enamel. See *Colors for ceramics and glass*; *Enamels*.

A second important ceramic use for titanium dioxide is in the field of components for electronic equipment. Titanium dioxide capacitors are widely used in radio and television sets and, because of their efficiency, they find use in miniature units such as hearing aids. Dielectric components are fabricated by pressing high-purity rutile powder into the desired shape and then heating the pressed part until the particles sinter together. Since moisture has an adverse effect on the electrical properties of most materials, the parts are fired at a high temperature to eliminate porosity. Additives are often added to the titanium dioxide to alter its electrical characteristics or its processing properties.

Mineral rutile finds use as an additive to welding-rod coatings and as a batch addition in the manufacture of glass fiber. The natural material is utilized in these instances since the iron impurities present are not objectionable in the finished product.

A recent development in the titanium field is the production of large synthetic rutile crystals. Since these crystals are very pure, their properties differ from the naturally occurring rutile crystals. These synthetic crystals are formed by a process similar to the well-known Verneuil process which is used to manufacture synthetic sapphires and rubies (see *Gems, synthetic*). Rutile single crystals are formed by dropping titanium dioxide particles through an oxy-hydrogen flame and allowing the molten droplets to fall onto a movable pedestal. As the pedestal is withdrawn from the hot zone of the furnace, the molten material solidifies in the form of a single crystal. These crystals are grown to a weight of approximately 20 g. Their principal use is as a synthetic gem material. Due to the exceptionally high index of refraction, gemstones cut from this material are very brilliant and exhibit an unusual amount of spectral color.

Inorganic Titanates

The compounds generally referred to as titanates are believed on the basis of x-ray analysis to be multiple oxides rather than true salts (see Vol. 9, p. 687). There is no evidence for the existence of titanate anions. These compounds range in composition from the metatitanates, M_2TiO_3 or $M_2O.TiO_2$, and the orthotitanates, M_4TiO_4 or $2M_2O.TiO_2$, to the highly acid titanates such as $M_2Ti_6O_{11}$ or $M_2O.5TiO_2$, where M is a univalent metal. The titanates are generally prepared by mixing the appropriate quantities of titanium dioxide or hydrous titanium oxide with the desired metal oxide, hydroxide, carbonate, or salts which convert to oxides upon calcination, and then heating the mixture at elevated temperatures to effect the reaction. The temperature of calcination may vary from about 160°C., for some of the strong bases such as those of the alkali metals, to 1700°C., for the more refractory oxides.

Titanates of the alkali, alkaline earth, and heavy-base metals are known. The alkaline earth and heavy-metal titanates are very stable compounds. They are insoluble in water but are decomposed by acids. These compounds have been proposed for use as pigments, but only lead titanate, $PbTiO_3$, has been employed commercially for this purpose. They find their greatest use in the ceramic field, in the manufacture of porcelain enamels, ceramic dielectrics, temperature-sensitive resistors, and photoconductors. The alkali metal titanates are less stable compounds. They tend to hydrolyze in water and dissolve readily in acids.

Alkali Metal Titanates.

Lithium Titanates. Lithium metatitanate, Li_2TiO_3, is a white solid of cubic structure, sp.gr. 3.42. Lithium dititanate, $Li_2Ti_2O_5$, is also cubic, sp.gr. 3.50. The orthotitanate, Li_4TiO_4, has been reported. The lithium titanates are prepared by heating appropriate amounts of titanium dioxide and lithium carbonate to approximately 950°C.

Potassium Titanates. Potassium metatitanate, K_2TiO_3, and potassium dititanate, $K_2Ti_2O_5$, are both white solids and melt at about 806 and 980°C., respectively. Hydrated compounds are also reported. These titanates are prepared by solid-state reaction of potassium carbonate or bicarbonate and titanium dioxide. The metatitanate may also be prepared by heating mixtures of hydrous titanium oxide and potassium hydroxide to 160–170°C.

Sodium Titanates. There are three principal sodium titanates: Na_2TiO_3, m.p. 1030°C., $Na_2Ti_2O_5$, m.p. 985°C., and $Na_2Ti_3O_7$, m.p. 1128°C. All are white, slightly hygroscopic, crystalline solids, and melt congruently. Several other sodium titanates are referred to in the literature. The sodium titanates are obtained by heating appropriate mixtures of sodium hydroxide or carbonate and hydrous titanium oxide or titanium dioxide (29).

Alkaline Earth Metal Titanates.

Interest in, and uses for the alkaline earth titanates, have developed considerably since 1940. In general, these compounds exhibit unique electrical characteristics which make them well suited for electrical applications. Few of these compounds occur in nature and those that are found in nature are not suitable for electrical use because of their high impurity content. For this reason, all of these compounds are synthesized, usually by mixing the oxides or other salts of the alkaline earths with titanium dioxide in the proper stoichiometric proportions and heating the mixture at elevated temperatures until conversion to the desired titanate is completed.

Barium Titanate. Barium titanate, $BaTiO_3$, formula weight 233.26, melting point approximately 1625°C., is a crystalline solid having five crystal modifications: hexagonal, cubic, tetragonal, orthorhombic, and trigonal. The tetragonal modification, which is the important form electrically, has a specific gravity of about 6 and a very high dielectric constant.

The ceramic form of barium titanate is usually prepared by intimately mixing the proper amounts of barium carbonate and titanium dioxide and heating the mixture at 1300°C. until complete reaction has taken place. When commercial ceramic bodies are produced, the sinter is ground to a small particle size with small amounts of other constituents which are added to facilitate manufacture or to modify the characteristics of the finished product. The mass is formed into the desired shape by pressing or casting and then fired. Considerable care must be exercised to control the firing cycle and the furnace atmosphere to obtain satisfactory crystal growth within the mass and to obtain products of maximum density. These factors exercise an appreciable effect on the electrical properties.

Barium titanate, when subjected to a high d.c. electric field, becomes polarized not only while the field is maintained but permanently. This effect can be produced only at temperatures below its Curie point, 120°C., for at higher temperatures barium titanate is transformed from the tetragonal to the cubic form and the effect is destroyed.

Polarized barium titanate masses exhibit two unusual properties. They are ferroelectric (show spontaneous polarization that can be reversed by the application of an electric field), and they are piezoelectric (produce an electric field as a result of pressure). Because of this, barium titanate elements find use in phonograph pickups, underwater detection devices, electronic circuits, and equipment for ultrasonics, (*q.v.*). The high dielectric constant of barium titanate and its change with temperature also make the material useful as high-value capacitors of small dimensions and as temperature-compensating elements (31).

Calcium Titanates. Calcium titanate (perovskite), $CaTiO_3$, is a white solid, m.p. 1980°C., sp.gr. 4.02. Other calcium titanates, such as $3CaO.2TiO_2$ and $3CaO.TiO_2$, have been reported. Synthesized calcium titanate is often used as an additive to a ceramic barium titanate body to alter its electrical characteristics.

Magnesium Titanates. Three magnesium titanates are known: the metatitanate, $MgTiO_3$, the orthotitanate, Mg_2TiO_4, and the dititanate, $MgTi_2O_5$. The metatitanate, $MgTiO_3$, is the most commonly utilized form of magnesium titanate. It is a white solid, rhombohedral in structure, sp.gr. 3.84. Its principal use is as an additive to ceramic dielectric components.

Magnesium orthotitanate, Mg_2TiO_4, crystallizes in the cubic system, m.p. 1840°C., sp.gr. 3.53. Magnesium dititanate, $MgTi_2O_5$, crystallizes in the orthorhombic system, m.p. 1645°C.

Strontium Titanate. Strontium titanate, $SrTiO_3$, is a white crystalline cubic solid, m.p. 2080°C., sp.gr. 5.13, Knoop hardness 595. This material, like rutile, has a high index of refraction ($n_D = 2.409$) and a high dielectric constant, 310. Strontium titanate is used as an additive to barium titanate bodies since it has the effect of lowering the Curie point and changing the temperature coefficient.

Single crystals of strontium titanate were grown in 1952 for optical and gem purposes. These crystals were found to transmit light having wave lengths of from 395 to over 1700 millimicrons. Their dispersion ($n_F - n_C$) was found to be 0.108.

Other Titanates.

Aluminum Titanate. Aluminum titanate (tielite), Al_2TiO_5, is a white solid. It exists in α- and β-modifications, with the α-form stable above 1820°C. and melting at about 1860°C. The material is artificially prepared by sintering or fusing the oxide components.

Cadmium Titanate. Cadmium titanate, $CdTiO_3$, is a yellow solid and crystallizes in the orthorhombic system, sp.gr. 6.5. A transition to the cubic form occurs at 1050°C.

Cobalt Titanates. Cobalt metatitanate, $CoTiO_3$, is a green solid, rhombohedral in structure, sp.gr. 5.00. It is obtained by heating cobalt carbonate and titanium dioxide (molar ratio $1CoCO_3:1TiO_2$) at 900°C. Cobalt orthotitanate, Co_2TiO_4, is a greenish-black solid having the cubic structure, sp.gr. 5.07.

Iron Titanates. *Ferrous metatitanate*, $FeTiO_3$, sp.gr. 4.72, is rhombohedral in structure, and opaque black in color, with submetallic luster. It occurs in nature as the mineral ilmenite, which is used extensively in the manufacture of titanium oxide pigments. It has been prepared artificially by heating a mixture of ferrous oxide and titanium dioxide, in a sealed silica tube for several hours at 1200°C., and also by reduction at 450°C. of a mixture of ferric oxide and titanium dioxide. The melting point is reported to be about 1470°C. (2,23).

Ferrous orthotitanate, Fe_2TiO_4, is orthorhombic, opaque, with a melting point near 1470°C. It has been prepared by fusing a mixture of ferrous oxide and titanium dioxide. *Ferrous dititanate*, $FeTi_2O_5$, is orthorhombic, and has been formed by heating ilmenite with carbon at 1000°C. The metallic iron formed in the reaction is removed leaving a composition which is essentially the dititanate.

Ferric titanate (pseudobrookite), Fe_2TiO_5, formula weight 239.60, is orthorhombic, and occurs to a limited extent in nature. It is the only compound which has been proved to exist in the system Fe_2O_3–TiO_2, and has been prepared by heating a mixture of ferric oxide and titanium dioxide in a sealed quartz tube at temperatures of 1000°C. or higher.

Lead Titanate. Lead titanate, $PbTiO_3$, formula weight 303.11, is a yellow solid, sp.gr. 7.52, and crystallizes from melts as orthorhombic, holohedral pyramids. It is prepared by reaction of the respective oxides in equimolar amounts at temperatures as low as 400°C. No other lead titanate compositions are known. Lead titanate has been used commercially as a pigment for paint formulations to impart color stability and durability to exterior coatings.

Manganese Titanates. Manganese metatitanate, $MnTiO_3$, is a yellow solid, hexagonal in structure, sp.gr. 4.54. It melts incongruently at 1360°C. Manganese orthotitanate, Mn_2TiO_4, is cubic in structure, m.p. 1455°C., sp.gr. 4.49.

Nickel Titanate. Nickel titanate, $NiTiO_3$, is a canary-yellow solid, rhombohedral in structure, sp.gr. 5.08.

Zinc Titanates. *Zinc orthotitanate*, Zn_2TiO_4, sp.gr. 5.12, is a white solid having the spinel structure and is obtained by heating zinc oxide and hydrous titanium oxide in the molar ratio of $2ZnO:1TiO_2$. The reaction begins at about 430°C., but a temperature of about 1000°C. is required to complete the reaction. Zinc orthotitanate forms a series of solid solutions with titanium dioxide extending to the composition $Zn_2TiO_4 . 1\frac{1}{2}TiO_2$. These solid solutions are not stable at elevated temperature and begin to dissociate at 775°C. into titanium dioxide and solid solutions poorer in titanium dioxide. The titanium dioxide that crystallizes from the solid solutions has the rutile structure.

A product corresponding to the composition of zinc metatitanate was found to be in reality a solid solution of zinc orthotitanate and titanium dioxide. While there are many references in the literature to the preparation of zinc metatitanate, $ZnTiO_3$, and other titanates such as $Zn_3Ti_2O_7$, $ZnTi_3O_7$, and $Zn_4Ti_5O_{14}$, the existence of these compounds has not been established with certainty.

Titanium Phosphates.

Titanium(III) Phosphate. Titanous phosphate is a purple hydrate of unknown composition which is soluble in dilute acids. Its solutions are relatively stable and resistant to hydrolysis. It may be prepared by adding sodium phosphate to either a titanium(III) sulfate or chloride solution, adding alkali to decrease the acidity until precipitation occurs, filtering, and washing.

Titanium(IV) Phosphates. *Titanium pyrophosphate*, TiP_2O_7, formula weight 221.86, m.p. 1490°C., is a white powder crystallizing in the cubic system and having a density calculated from x-ray data of 3.106. It is insoluble in water. It may be prepared by heating to 900°C. a mixture of one formula weight TiO_2, as hydrous titanium oxide, and one formula weight P_2O_5, as phosphoric acid.

Hydrous titanium phosphate is a gelatinous material of variable composition which, when properly prepared, is highly insoluble in acids. It may be prepared by adding an alkali phosphate to titanyl sulfate solution, filtering the hydrous titanium phosphate formed, leaching, and drying. Its insolubility in dilute sulfuric acid has led to some commercial interest for separating titanium from iron in ilmenite sulfate solutions. It has also been used in the dyeing and leather tanning industries.

Other titanium phosphates, such as $3TiO_2.P_2O_5.6H_2O$ and $2TiO_2.P_2O_5$, have been claimed to exist, but their composition has not been confirmed. There is no commercial interest in any of these phosphates.

Titanium Phosphide.

Titanium phosphide, TiP_n, where n varies from 0 to 0.94, is a material of variable phosphorus content for which no well-defined compounds have been established. It is a dark gray powder the density of which varies from 4.66 for $n = 0.26$ to 3.95 for $n = 0.94$. It has unusually high thermal stability. Thus, it does not decompose when heated in vacuum or a protective atmosphere at 1100°C. It is not attacked by any of the common dilute or concentrated acids, but it is oxidized in air on heating. It may be prepared by reaction of the elements at elevated temperature under controlled conditions or from titanium tetrachloride and phosphine at 750°C.

Titanium Silicates.

Titanium dioxide and silica form a eutectic composition at 89.5 weight per cent silica which melts at 1540°C. No compound formation has been observed in this system.

Calcium titanium silicate, $CaO.TiO_2.SiO_2$, formula weight 196.04, sp.gr. 3.497, is a monoclinic solid, which melts congruently at about 1380°C. It can be synthesized by heating a mixture of calcium carbonate, titanium dioxide, and silica. It exists in nature as the mineral *sphene* or *titanite* and has been proposed as a source material for the manufacture of titanium dioxide pigments. However, it has little commercial importance at present.

Titanium Silicides.

Titanium disilicide, $TiSi_2$, formula weight 104.08, has an orthorhombic structure, $a_0 = 8.23$, $b_0 = 4.773$, and $c_0 = 8.523$ A. The compound melts at 1540°C., and has a Knoop hardness of 618 kg./sq.mm. (100 g. load). The density is reported as 4.39 g./cu.cm., and the electrical resistivity as 123 microhm-cm. at room temperature. Titanium disilicide can be prepared by decomposing titanium tetrachloride on pure silicon powder and by electrolysis of fused salt baths of alkali fluosilicates and titanium dioxide.

The existence of **titanium monosilicide,** TiSi, has been established from an investigation of the Ti–Si system. The Knoop hardness of this compound is 1039 kg./sq.mm. (100 g. load).

The intermetallic compound **pentatitanium trisilicide,** Ti_5Si_3, has a hexagonal structure, $a_0 = 7.465$ and $c_0 = 5.162$ A. It melts at 2120°C., and has a Knoop hardness of 986 kg./sq.mm. (100 g. load). These products can be prepared by reaction of titanium and silicon powders at elevated temperatures in a protective atmosphere.

Titanium Sulfates.

Titanium(III) sulfate (titanous sulfate), $Ti_2(SO_4)_3$, formula weight 384.01, is a green, crystalline powder. On heating in air it is gradually transformed to titanium dioxide. It is soluble in dilute acids to form purple solutions. It may be prepared by reducing titanyl sulfate solution electrolytically until the titanium is in the trivalent state, evaporating, and filtering the hydrated crystals which are formed. These crystals are dissolved in sulfuric acid which is then heated to about 200°C. to yield crystals of the desired product. The hydrated sulfate, $3Ti_2(SO_4)_3.H_2SO_4.25H_2O$, is a purple, crystalline powder which, when heated in air, first gives off water and then sulfuric acid. It is soluble in water yielding a stable, purple solution. It may be prepared by reducing titanyl sulfate solution electrolytically until the titanium is in the trivalent state, evaporating the solution, and removing the resultant crystals by filtration.

Titanium(IV) sulfate, $Ti(SO_4)_2$, formula weight 240.04, is a white, hygroscopic powder. It may be prepared by treating titanium tetrachloride with sulfur trioxide in sulfuryl chloride. It is believed to occur as an intermediate in the conversion of ilmenite to titanium–iron sulfate solution. Hydrates $Ti(SO_4)_2.9H_2O$, $Ti(SO_4)_2.4H_2O$ and $Ti(SO_4)_2.3H_2O$ have been reported.

Titanyl sulfate (titanium oxysulfate, basic titanium sulfate, titanium sulfate), $TiOSO_4$, formula weight 159.97, is a white, crystalline, hygroscopic powder. It is soluble in cold water but hydrolyzes very easily on warming the solution. When heated in air to 580°C., it decomposes to $2TiO_2.SO_3$, and at higher temperatures is finally transformed to titanium dioxide. It may be prepared by the controlled reaction between titanium dioxide and sulfuric acid or by heating anhydrous titanium sulfate to 500°C.

Titanyl sulfate dihydrate, $TiOSO_4.2H_2O$, is a white, needle-like, crystalline powder and is the most firmly established of the titanium sulfates. It dissolves slowly in cold water but hot solutions are unstable and hydrolyze. When heated in air, it loses water and then sulfur dioxide and finally forms titanium dioxide. It may be prepared by heating solutions of titanyl sulfate containing about 10% titanium dioxide and about 20–40% sulfuric acid until crystallization occurs. The crystals may be removed by filtration, washed with 40% sulfuric acid solution and acetone, and dried. There are many variations of this process. Commercial titanyl sulfate cake is made by treating one mole TiO_2 as hydrous titanium oxide with two moles H_2SO_4 as concentrated sulfuric acid. The solid cake formed consists mostly of titanyl sulfate and sulfuric acid. This product finds use in the dyeing industry as a mordant and for the preparation of reduced titanium sulfate solution useful in dye stripping. It is also used as a source material to prepare other inorganic titanium compounds. A monohydrate, $TiOSO_4.H_2O$, has been reported.

Titanium Sulfides.

A number of titanium sulfides have been described and their existence seems to be well established. As with the titanium oxides each phase is capable of existence over a wide range of composition, although the limits have not been well defined in all cases. There are no commercial uses for any of the titanium sulfides.

Titanium subsulfide, Ti_2S, formula weight 127.87, is a gray solid, sp.gr. 4.60. It is taken into solution by concentrated hydrochloric and sulfuric acids, is attacked by

concentrated nitric acid, but is insoluble in alkalies. It may be prepared by careful heating of mixtures of titanium metal and sulfur at 800–1000°C.

Titanium monosulfide, TiS, formula weight 79.97, is a dark brown solid probably crystallizing in the hexagonal system, sp.gr. 4.05. It is attacked by concentrated hydrochloric and nitric acids, is soluble in concentrated sulfuric acid, but is not attacked by alkalies. It may be prepared by reducing titanium disulfide with hydrogen at elevated temperatures, or by reaction of the elements under controlled conditions.

Titanium sesquisulfide, Ti_2S_3, formula weight 192.01, is a black crystalline solid, sp.gr. of 3.52. It is attacked by concentrated hydrochloric and nitric acids, is soluble in sulfuric acid, but is insoluble in alkalies. It may be prepared by reducing titanium disulfide with hydrogen, or by reaction of the elements at 800°C., followed by further heat treatment at elevated temperature.

Titanium disulfide, TiS_2, formula weight 112.04, is a bronze-colored solid crystallizing in the hexagonal system (cadmium iodide structure), sp.gr. 3.22. When heated in the absence of air, it gradually loses sulfur and forms lower sulfides, but when heated in moist air, it reacts readily with water to form titanium dioxide and hydrogen sulfide. It is completely dissolved by hot, concentrated sulfuric acid, is oxidized to titanium dioxide by concentrated nitric acid, but is not attacked appreciably by concentrated hydrochloric acid. In contrast to the other titanium sulfides it is decomposed by hot sodium hydroxide solution.

Titanium disulfide is prepared by the reaction of hydrogen sulfide and titanium tetrachloride at about 600°C. in a hot tube.

Titanium trisulfide, TiS_3, formula weight 144.11, is a graphite-like solid which probably occurs as a layer lattice, sp.gr. 3.22. It is soluble in hot, concentrated sulfuric acid and is attacked by hot, concentrated nitric acid to form titanium dioxide. It is also attacked by hot sodium hydroxide solution. It may be prepared by sulfurizing titanium disulfide or lower sulfides under pressure and then carefully removing the excess sulfur.

ORGANIC TITANIUM COMPOUNDS

The inorganic compounds of titanium have been studied since the time of Gregor (1790), but the first reference to organic compounds was not made until late in the 19th century. The number of known organic compounds is rapidly approaching the number of inorganic compounds although they have far less commercial significance.

The arrangement of electrons in the titanium atom is responsible for the peculiar properties of the organotitanium compounds. Thus, titanium and the other elements of group IVa of the periodic table do not exhibit the property of forming strong covalent bonds to carbon, whereas the metals of group IVb all form stable metal-carbon bonds readily. In the case of carbon, silicon, germanium, tin, and lead, the four valence electrons are found in the same principal quantum shell. Attachment of four groups to these metals leads to organometallic compounds in which each substituent occupies a corner of a tetrahedron.

In the case of titanium, the valence electrons are equally divided between the 3*d* and 4*s* subshells. This arrangement does not lead to a tetrahedral structure when four substituents are placed on a single titanium atom, but rather appears to tend toward structures in which the titanium atom is centrally located in a square with the four substituents at the corners of the plane. This configuration then permits the

close approach to the central titanium atom of other molecules leading to the development of bonding forces that vary from weak attractions to strong coordinate covalent bonds. Although titanium has a normal valence of four, it tends in all cases to exercise its full coordination number of six. The hexacoordinated titanium molecules possess an octahedral structure.

The electron configuration of titanium thus does not lead to structures similar to those derived from the metals of group IVb. In addition, this configuration does not permit ready formation of metal-carbon bonds. Hence, the best-known organic compounds of titanium are the derivatives of orthotitanic acid, that is, they contain Ti—O—C bonds, although a few well-defined compounds containing Ti—C bonds are known, such as phenyltitanium triisopropylate, $C_6H_5Ti(OC_3H_7)_3$, and biscyclopentadienyltitanium dihalides, as $(C_5H_5)_2TiCl_2$ (13,30). These, however, are unusual structures and the potential existence of simple titanium alkyls is highly improbable.

Organic Titanates

Methyl titanate, $Ti(OCH_3)_4$ or $Ti(OCH_3)_4.CH_3OH$, is a white, semicrystalline solid, which hydrolyzes rapidly on exposure to moist air. The melting point is in excess of 200°C. and the sublimation point 300°C. at 18 mm. It may be prepared by the reaction of sodium methylate with titanium tetrachloride or by boiling the tetraethyl ester with absolute methanol (3).

Ethyl titanate, $Ti(OC_2H_5)_4$, is a light yellow liquid, $b_{8.5}$ 145°C., b_{156} 205°C., and is miscible with most inert organic solvents. However, it reacts with solvents containing active hydrogen atoms such as alcohols and acids, and hydrolyzes very rapidly in the presence of moisture, yielding partially hydrolyzed ethyl titanate and, eventually, hydrous titanium oxide. It is prepared by the reaction of sodium ethylate with titanium tetrachloride.

Isopropyl titanate, $Ti(OC_3H_7)_4$, is a colorless mobile liquid which fumes on exposure to moist air, $b_{7.5}$ 97°C. It forms a crystalline solid at temperatures below 20°C. The preparation involves reaction of titanium tetrachloride with four moles of isopropyl alcohol in the presence of an equal number of moles of ammonia which acts as an acceptor for the hydrogen chloride released. It has been used as a catalyst for aldol condensations and also enters readily into the Meerwein-Pondorf reactions (see Vol. **1,** p. 628).

***n*-Butyl titanate,** $Ti(OC_4H_9)_4$, formula weight 340.35, is probably the best-known of the organotitanium compounds. It is a nearly colorless, oily liquid, b_2 160–62°C. It reacts with acetone, but is miscible with all common organic solvents except certain amides and nitriles, such as formamide and acetonitrile. It is not miscible with liquid ammonia.

It is best prepared by the reaction of titanium tetrachloride with *n*-butyl alcohol in the presence of ammonia. The ammonium chloride is filtered or centrifuged from the product and the high-boiling ester distilled under reduced pressure (40).

Like the lower-molecular-weight members of the series of alkyl titanates, *n*-butyl titanate hydrolyzes on exposure to moist air, but does so at a reduced rate. The hydrolysis products exhibit increasing molecular weight and complexity as the reaction proceeds and are termed condensed titanates. They probably contain chains of alternating titanium and oxygen atoms. These condensed esters are also obtained upon heating *n*-butyl titanate to 200–250°C., or by partial pyrolysis of the butyl titanates.

The condensed esters vary from viscous oils to semicrystalline solids depending on the number of alkoxy groups removed in the reaction. They react similarly to the tetra-esters but at a reduced rate (4).

n-Butyl titanate and its condensed derivatives are used in the preparation of heat-resistant coatings for metals. When pigmented with leafing types of pigments, especially aluminum powder, paints are obtained that resist temperatures in excess of 600°C.

Besides its reaction with water, *n*-butyl titanate also reacts with alcohols and acids in an ester-exchange type of reaction. This exchange proceeds rapidly and without catalysts. Thus, *n*-butyl titanate can serve as the source material for the preparation of many other titanium derivatives of acids and alcohols. It also can react by this mechanism with macromolecular alcohols and acids, such as cellulosics and resins, reducing the sensitivity of these materials to organic and aqueous solvents. When applied to fabric and paper, a water-repellent action is exhibited. The addition of butyl titanate in small quantities to oleoresinous coatings has a marked accelerating influence on their drying rate and results in increased hardness.

Miscellaneous alkyl titanates can be formed from a wide variety of alcohols other than those mentioned. The preparation may be from titanium tetrachloride in the presence of a base (usually ammonia) or, more conveniently, from a simpler ester such as *n*-butyl or isopropyl titanate. The method employing titanium tetrachloride and ammonia fails in the case of tertiary alcohols. The properties of these materials are similar to those of the esters described in more detail. In general, the higher-molecular-weight alcohol esters exhibit increased stability towards hydrolysis and ester exchange.

Aryl Titanates. Titanium tetrachloride reacts with phenols to yield a series of phenoxytitanium chlorides, and eventually, with the complete substitution of chlorine atoms, the tetraaryl titanates. This reaction proceeds to completion only in the presence of a base such as ammonia or an amine. All of these materials are intensely colored, the colors varying from orange to red. In the case of phenol, the maximum color is exhibited by the monophenoxytitanium trichloride, $C_6H_5OTiCl_3$.

Phenyl titanate, $Ti(OC_6H_5)_4$, formula weight 420.3, m.p. 153–54°C., is a bright red crystalline compound which is soluble in the common organic solvents but hydrolyzes in the presence of moisture. It associates strongly with oxygenated organic molecules, forming orange to orange-red crystalline complexes.

Other Compounds

Because of its unfilled 3*d* shell of electrons, titanium is capable of forming coordination compounds with a variety of organic agents. Among the latter are amines, diamines, amino alcohols, polyols, hydroxy acids, polybasic acids, and β-diketones. Most of these compounds are crystalline or semicrystalline yellow solids, although those derived from phenolic and enolic substances are red or red-orange.

A large number of unstable addition-type complexes are formed when titanium tetrachloride is treated with organic substances containing oxygen or nitrogen. These complexes usually consist of one or two moles of the organic residue per mole of titanium tetrachloride, although other molar ratios are found in a few cases. The ability of titanium tetrachloride to form such coordination compounds is probably responsible for its pronounced activity as a Friedel-Crafts type of catalyst.

Like the alcohols and phenols, organic acids also form derivatives of orthotitanic and metatitanic acids. These derivatives, termed *titanium acylates*, are usually not definite compounds and exhibit properties typical of high-molecular-weight complexes, probably containing chains of alternate titanium and oxygen atoms. Titanium tetraacylates apparently do not exist.

Titanium acylates are most commonly prepared by the reaction of a metal salt of the organic acid with titanium tetrachloride or titanyl sulfate. They also may be prepared by the ester-exchange reaction involving an alkyl titanate and one or two moles of the acid. Titanium chloride acylates, in which the chlorine is only partially replaced by acyl groups or oxygen, are also known and result from the reaction of an acid with titanium tetrachloride in the vapor phase (46) or in an inert solvent.

The titanium acylates are hydrolyzed by water but are generally soluble in most organic solvents. The derivatives of the higher fatty acids, which are soluble in nonpolar solvents and oils, have been suggested for use as paint driers.

There are also a large number of stable complexes containing either one or two molecules of a hydroxy or dibasic organic acid per molecule of orthotitanic acid. Among these are titanium citrate, lactate, tartrate, salicylate, and gluconate. Most of the complexes are soluble in dilute alkali and have found limited use in the mordanting and dye-stripping operations of the textile industry.

An equimolar complex of orthotitanic acid and phthalic acid termed "titanium phthalate" has been used as an extender pigment in chemical-resistant paint. This complex is prepared by the reaction of titanyl sulfate with a solution of an alkali salt of phthalic acid. The white precipitate so formed contains some hydrous titanium oxide.

Titanium oxalate, which exists as the anionic complex $[TiO(C_2O_4)_2]^{2-}$, has found use commercially in the tanning of leather and in various dyeing operations. It is prepared in aqueous solution by the reaction of an alkali metal oxalate with titanium sulfate or chloride.

Bibliography

(1) Barksdale, J., *Titanium, Its Occurrence, Chemistry and Technology*, Ronald Press, N.Y., 1949.
(2) Barth, T. F. W., and Posnjak, E., *Z. Krist.*, **88**, 265–70 (1934).
(3) Bischoff, F., and Adkins, H., *J. Am. Chem. Soc.*, **46**, 256–59 (1924).
(4) Boyd, T., *J. Polymer Sci.*, **7**, 591–602 (1951).
(5) Bumps, E. S., Kessler, H. D., and Hansen, M., *Trans. A.S.M.*, **45**, 1008–25 (1953).
(5a) Bunting, E. N., *Bur. Standards J. Research*, **11**, 719 (1933).
(6) Depew, H. A., *Trans. Am. Inst. Chem. Engrs.*, **41**, 711 (1945).
(7) DuMont, C. S., *Bibliography on Titanium—Its Production, Properties, and Uses (1900–1946)*, Battelle Memorial Institute, Columbus, Ohio, 1947.
(8) Ehrlich, P., *Z. Elektrochem.*, **45**, 362–70 (1939).
(9) Gibb, T. R. P., Jr., and Kruschwitz, H. W., Jr., *J. Am. Chem. Soc.*, **72**, 5365 (1950).
(10) Gibb, T. R. P., Jr., McSharry, J. J., and Bragdon, R. W., *J. Am. Chem. Soc.*, **73**, 1751 (1951).
(11) Gillson, J. L., "Titanium," in *Industrial Minerals and Rocks*, 2nd ed., Am. Inst. Mining Met. Engrs., 1949, pp. 1042–73.
(12) Gmelin, 8th ed., 1951, System-Nummer 41.
(13) Herman, D. F., and Nelson, W. K., *J. Am. Chem. Soc.*, **75**, 3877–87 (1953).
(14) Jaffee, R. I., and Campbell, I. E., *J. Metals*, **1**, *Trans.*, **185**, 646–54 (1949).
(15) Kraitzer, I., McTaggart, F., and Winter, G., *Australia, Dept. Munitions, Paint Notes*, **2**, 304–9, 348–56 (1947).
(16) McQuillan, A. D., *Proc. Roy. Soc. (London)*, **A204**, 309–23 (1950).
(17) McQuillan, A. D., *J. Inst. Metals*, **79**, 371–78 (1951).

(18) Minerals Industry Survey, U.S. Dept. of the Interior, *Bur. Mines, Mineral Market Reports*, MMS-2305 (July 28, 1954).
(19) *Minerals Yearbook*, U.S. Dept. of the Interior, Bureau of Mines, 1942–1951.
(20) National Lead Co., Titanium Division, Research Laboratory, Unpublished data.
(21) Naylor, B. F., *J. Am. Chem. Soc.*, **68**, 1077–80 (1946).
(22) O'Brien, W. J., *Chem. Eng. Progress*, **44**, 809–14 (1948).
(23) Posnjak, E., and Barth, T. F. W., *Z. Krist.*, **88**, 271–80 (1934).
(23a) Schroeder, A., *Z. Krist.*, **66**, 493 (1928); **67**, 485 (1928).
(24) Schwarzkopf, P., and Kieffer, R., *Refractory Hard Metals*, Macmillan, N.Y., 1953, pp. 276–280.
(25) Skinner, G., Johnston, H. L., and Beckett, C., *Titanium and Its Compounds*, Herrick L. Johnston Enterprises, Columbus, Ohio, 1954.
(26) Swanson, H. E., and Tatge, E., *Natl. Bur. Standards, Circ.* **539**, Vol. I, pp. 44–47, June 15, 1953.
(27) *The Handbook*, Titanium Pigment Corp., N.Y., 1949.
(28) *"Titanox" Pigments—Properties and Uses*, Titanium Pigment Corp., N.Y., 1949.
(29) Washburn, E. W., and Bunting, E. N., *Bur. Standards J. Research*, **12**, 239 (1934).
(30) Wilkinson, G., Pauson, P. L., Birmingham, J. M., and Cotton, F. A., *J. Am. Chem. Soc.*, **75**, 1011–12 (1953).
(31) Von Hippel, A., *Revs. Modern Phys.*, **22**, 221–37 (1950).
(32) U.S. Pat. Re. 18,790 (April 4, 1933), W. Mecklenburg (to Krebs Pigment and Color Corp.). Reissue of 1,758,528 (May 13, 1930).
(33) U.S. Pat. Re. 18,854 (May 30, 1933), J. Blumenfeld (to Krebs Pigment and Color Corp.). Reissue of 1,795,467 (May 10, 1931).
(34) U.S. Pat. 1,889,027 (Nov. 29, 1933), W. F. Washburn (to National Lead Co.).
(35) U.S. Pat. 1,906,730 (May 2, 1933), W. F. Washburn and L. Aagaard (to National Lead Co.).
(36) U.S. Pat. 2,042,436 (May 26, 1936), S. S. Svendsen (to Burgess Titanium Co.).
(37) U.S. Pat. 2,046,054 (June 30, 1936), J. E. Booge (to Du Pont).
(38) U.S. Pat. 2,098,055 (Nov. 2, 1937), F. H. McBerty (to Du Pont).
(39) U.S. Pat. 2,143,850 (Jan. 17, 1939), B. W. Allan (to American Zirconium Corp.).
(40) U.S. Pat. 2,187,821 (Jan. 23, 1940), J. Nelles (to I. G. Farbenind.).
(41) U.S. Pat. 2,342,483 (Feb. 22, 1944), C. M. Olson (to Du Pont).
(42) U.S. Pat. 2,389,026 (Nov. 13, 1945), W. J. Cauwenberg and C. A. Tanner (to American Cyanamid Co.).
(43) U.S. Pat. 2,559,638 (July 10, 1951), I. J. Krchma and H. H. Schaumann (to Du Pont).
(44) U.S. Pat. 2,635,946 (April 21, 1953), R. Weber and W. Frey (to Saeurefabrik Schweizerhall).
(45) U.S. Pat. 2,670,275 (Feb. 23, 1954), C. M. Olson and J. N. Tully (to Du Pont).
(46) U.S. Pat. 2,670,363 (Feb. 23, 1954), J. P. Wadington (to National Lead Co.).
(47) Brit. Pat. 707,389 (April 14, 1954), G. L. Cabot.

L. R. Blair, H. H. Beacham, and W. K. Nelson

TITER. See *Fats and fatty oils*, Vol. 6, p. 152.

TNB, $C_6H_3(NO_2)_3$; **TNT,** $CH_3C_6H_2(NO_2)_3$. See *Explosives (high)*, Vol. 6, pp. 42, 43.

TOBACCO

Tobacco belongs to the large family of plants known as the *Solanaceae*, also called the potato or nightshade family, and to the genus *Nicotiana*. Among approximately sixty species of *Nicotiana*, *N. tabacum* represents the bulk of the tobacco of commerce. One other species, *N. rustica*, is grown commercially in India and in the U.S.S.R., where it is known as Makhorka. According to Gage (13) this was the product which was being cultivated by the Indians of eastern North America at the time of its discovery. Seeds of the milder *N. tabacum* were introduced from the West Indies about 1612.

By 1531, less than 40 years after the discovery of America, Spaniards were cultivating the crop in Santo Domingo. By 1560, it was being grown commercially in Cuba and Venezuela and by about 1600 in Brazil. Tobacco from Spanish settlements had come into use in Europe and the British Isles at least 40 years before the colony of Jamestown was founded in 1607. By 1600 or 1605, mariners and traders had introduced tobacco into China, Japan, South Africa, and many other distant lands.

Tobacco is now grown in most of the cultivated areas of the world and is a major crop in many countries. Many excellent reports of tobacco culture are available (1,3,5,14,22,32,36). Table I shows world production of tobacco (30).

TABLE I. Estimated World Production of Tobacco.

By continents	Production, million lb.		
	1947–51 (av.)	1952	1953[a]
Asia (excluding U.S.S.R. and Manchuria)	2,930	2,800	2,923
North America	2,459	2,640	2,441
Europe (including U.S.S.R. in Asia)	1,218	1,101	1,237
South America	380	407	436
Africa	236	268	275
Oceania	9	13	12
Total world (excluding Manchuria)	7,231	7,230	7,324
Leading producing countries			
United States	2,083	2,255	2,046
China	1,425	1,300	1,300
India	547	459	491
U.S.S.R.	450	450	450
Brazil	233	237	262
Turkey	194	201	260
Japan	208	211	247
Pakistan	157	167	166
Greece	113	87	138
Italy	168	136	136
Canada	129	140	135
France	109	105	116
Southern Rhodesia	85	100	106
Indonesia	62	111	105
Burma	89	100	101

[a] Preliminary.

Tobacco yields an income of $1,124,000,000 (1952) to about 531,900 growers (1950 census) in the U.S. and is fourth in importance among all field crops from the standpoint of cash receipts to farmers. Estimated expenditures for tobacco products in 1952 amounted to $5.0 billion which includes federal, state, and local excise taxes.

Federal excise taxes for 1952 were $1,661,800,000. State excise taxes for the fiscal year 1952–53 (not available on a calendar year basis) were $468,260,000. Federal income taxes paid by tobacco manufacturers and leaf dealers amounted to $131,419,000 in 1950. In addition, receipts from import duties on tobacco and tobacco products totalled $16,200,000, (1952–53). Leaf exports in 1952 were valued at $246,000,000 ranking third among agricultural exports (29,31).

Types Used in American Industry

Environmental and genetic factors and manufacturing requirements have operated to separate cultivated tobaccos into distinct types. Prominent among the factors that determine type characteristics are: (*1*) character of the soil; (*2*) climate; (*3*) variety of seed; (*4*) methods of cultivation, fertilization, and harvesting; and (*5*) method of curing. The association between soil, seed, climate, and cultural and curing practices is so close and has such a determining effect upon the type produced as to preclude, as a general rule, the duplication of any given type in a new environment (13).

Flue-cured is the most important domestic type, exceeding in acreage, poundage, and value all other types combined. Its seed is derived from the original Orinoco from South America from which a large number of varieties have been developed. Beginning about 1940, varieties resulting from crosses with cigar wrapper types and wild varieties from South America and other parts of the world have been introduced to meet the threat of diseases. Varieties with still higher resistance are being developed from crosses with *N. glutinosa*, *N. longiflora*, and other species of *Nicotiana*. Flue-cured is grown on soils of medium fertility. As the name implies, the leaves are cured with heat. The color ranges from lemon and orange for the better cigaret grades to red and brown for the noncigaret grades. The principal use of flue-cured is in cigarets. About one-third of the annual production is exported.

Burley, a light air-cured type and second in importance of all the types grown in the U.S., originated as a mutant from a local variety known as Red Burley. The resultant White Burley is now synonomous with Burley. Substantial progress in the development of varieties resistant to diseases was achieved in 1935. As with flue-cured, intensive breeding for disease resistance and improved plant type is in progress. Burley thrives on fertile limestone soil, especially that of phosphatic origin. It is normally cured on the stalk, without heat, except as may be necessary to prevent "shed burn," a form of fungicidal decomposition. There has been a trend in recent years among small growers to detach, or prime, the bottom leaves. The cured leaves from the lower portion of the Burley stalk are light tan in color and very thin. They become progressively darker and heavier toward the top of the plant. Burley finds uses in domestic cigarets, pipe mixtures, and chewing tobacco; relatively small amounts are exported.

Maryland, also a light air-cured type, is grown on light-bodied soils in a restricted area. It has not changed much since colonial days and is thought to be descended from Sweet Scented which, with Orinoco, was widely grown by the early colonists. The cured leaf is of a dry, porous nature, relatively thin, with good combustibility. Maryland finds use in domestic cigarets, for export, and in scrap-filled cigars.

Turkish, or Oriental tobacco, is grown principally on soils of low fertility in semi-arid regions of Turkey and Greece. Culture of tobacco in these countries began shortly after 1700 with seed from America. These tobaccos are prized for their distinctive aroma and flavor, and are characterized by very small leaf size. The three

major types are Smyrna, Samsun, and Macedonian. Smyrna is grown in the southwestern part of Turkey in the vicinity of what is now Ismir. It is the mildest of the three classes and represents the largest production. Samsun is grown in the northern part of Turkey in areas bordering on the Black Sea. It has heavier aroma than Smyrna and Macedonian. The sugar content is the lowest of the three types, the total nitrogen is highest, and the nicotine content is intermediate. Macedonian is grown in that portion of Greece which was formerly Macedonia. Macedonian enjoys a reputation for very fine aroma. Turkish tobaccos are imported in large volume for use in cigaret blends, and comprise about 7% of the total leaf used in manufacture of cigarets.

Dark Air-Cured Types. One Sucker and Green River represent distinctly different types. These types are grown on heavy soil and are cultivated in a manner conducive to heavy body and high nicotine content. They find use primarily in chewing tobaccos with lesser amounts used in snuff, pipe mixtures, and exports. One Sucker also finds limited use in scrap-filled cigars. Sun-cured derives its name from the former practice of hanging the tobacco in the sun during a part of the curing process. It is used in the manufacture of plug chewing tobacco.

Fire-Cured. The fire-cured types are grown on fertile soil, spaced widely, and topped low in order to produce a heavy-bodied leaf. They are smoked over slow-burning fires during curing. Their principal use is in the manufacture of snuff, but there is a limited export trade with Africa in the unusual product known as Black Fat, or Dark African, which results from a drastic processing of the fire-cured and One Sucker types. Small quantities are used in the manufacture of Italian-type cigars.

Cigar tobaccos consist of three kinds according to usage in cigar manufacture. These are: *filler*, which makes up the "bunch," the bulk of a cigar; *binder*, leaf of good size, flexibility, strength, and combustibility, used to form the bunch and hold it in shape; and *wrapper*, thin leaf of good strength, elasticity, and appearance, used as the outer covering. In general, each of the three kinds constitutes a type or types grown especially for the purpose, although a certain amount of binder may be selected from filler types and from wrappers. Filler tobaccos never make satisfactory wrappers and, conversely, wrappers do not make good filler. Cigar tobaccos are grown extensively in the West Indies, being first grown in Santo Domingo and later in Cuba, whose soils and climate combine with cultural and curing practices to produce the world's most aromatic cigar tobaccos. Puerto Rican tobaccos, shipped into the U.S. chiefly for cigar filler, are similar to Cuban fillers, but are much milder and less aromatic. Although sometimes used alone, with binder and wrapper from other sources, these tobaccos are generally blended with other filler types.

Soon after 1800, the production of cigars and of cigar leaf began in the U.S., originating in the Connecticut Valley and to some extent in Pennsylvania. Cigar factories were opened in Suffield and East Windsor, Connecticut, in 1810, using locally grown tobacco. With the increase in cigar production, a more suitable type, Maryland Broadleaf, was introduced about 1833. From this developed Connecticut Broadleaf, a binder type in present use. The second Connecticut binder type, Havana Seed, originated shortly after the Civil War with seed introduced from Cuba. From these beginnings grew the highly specialized cigar-type producing areas. Using Connecticut Havana Seed, a binder-growing section was developed in Wisconsin, which now vies with Connecticut in production of this type. Likewise with seed from Connecticut, the filler-producing areas of Pennsylvania and Ohio were flourishing by 1900.

The most highly specialized type of tobacco is the cigar wrapper, which in the U.S. is grown only in the Connecticut Valley and in a small area of north Florida and south Georgia. Around 1900 certain growers of the Florida area began to grow the leaf under slat or cheesecloth shades. This innovation was rapidly adopted for growing wrapper in both Florida and Connecticut and ultimately became the only method of growing this type, which is now called shade-grown.

In addition to cigar tobaccos from the West Indies, important types are imported from the Philippines and the tropical islands of Sumatra and Java.

Other Types. Miscellaneous types of minor importance include Perique, grown in Louisiana and used for flavoring pipe mixtures; Latakia, imported from Syria for use in some cigarets and pipe mixtures; and Georgia-Florida sun-grown, a cigar binder type.

Tables II and III show exports and imports of major types of tobacco (29).

TABLE II. Production and Exports of Major Types of Tobacco.

(Millions of pounds, crop year basis.)

Type	Production		Exports, estimated farm sales weight	
	1947–51 (av.)	1952[a]	1947–51 (av.)	1952[a]
Flue-cured, types 11–14	1,246	1,365	422	416
Burley, type 31	553	650	34	29
Maryland, type 32	39	40	8	8
Dark air-cured, types 35–37	34	34	9	6
Fire-cured, types 21–24	70	58	34	30
Cigar leaf, types 41–62[b]	141	107	8	9
Puerto Rican filler, type 46	27	34	3	<1

[a] Preliminary.
[b] Excludes Puerto Rican.

TABLE III. Imports of Major Classes of Tobacco.

(Millions of pounds, fiscal year basis.)

Class	Imports	
	1948–49 to 1951–52 (av.)	1952–53[a]
Turkey	49	56
Greece	11	15
Total cigaret leaf	70	78
Total cigar leaf	23	28

[a] Preliminary.

Chemical Composition of Major Types

The four major cigaret types of tobacco, flue-cured, Burley, Maryland, and Turkish, exhibit characteristic differences in leaf composition as shown in Table IV. Flue-cured, types 11–14, is characterized by high carbohydrate and relatively low nitrogen and mineral contents. Malic acid is the principal nonvolatile acid and glutamine the principal amide. Burley, type 31, has considerably less carbohydrate and more nitrogen and mineral matter than flue-cured and is intermediate in chemical composition between Maryland and the cigar types. Maryland has a high carbohydrate content but very little reducing sugar. It is further charac-

terized by a low nitrogen content as compared with other air-cured types. Its mineral content approaches that of Burley.

Turkish tobacco shows characteristic variations among types and districts (18). It has a moderate level of reducing sugars which is, typically, about half that of flue-cured. The nicotine content is lowest of the cigaret types and represents a relatively small fraction of the total nitrogen. The volatile oils and resins are abundant and have intense and characteristic aroma. The resins differ from those of other types in their higher content of esters of fatty acids containing five and six carbon atoms.

TABLE IV. Representative Analyses of Cigaret Tobaccos.

(Leaf web after aging, moisture-free basis.)

Component	Flue-cured, type 13	Burley, type 31	Maryland, type 32	Turkish[a]
Total volatile bases as ammonia, %	0.282	0.621	0.366	0.289
Nicotine, %	1.93	2.91	1.27	1.05
Ammonia, %	0.019	0.159	0.130	0.105
Glutamine as ammonia, %	0.033	0.035	0.041	0.020
Asparagine as ammonia, %	0.025	0.111	0.016	0.058
α-Amino nitrogen as ammonia, %	0.065	0.203	0.075	0.117
Protein nitrogen as ammonia, %	0.91	1.77	1.61	1.19
Nitrate nitrogen as NO_3, %	Trace	1.70	0.087	Trace
Total nitrogen as ammonia, %	1.97	3.96	2.80	2.65
pH	5.45	5.80	6.60	4.90
Total volatile acids as acetic acid, %	0.153	0.103	0.090	0.194
Formic acid, %	0.059	0.027	0.022	0.079
Malic acid, %	2.83	6.75	2.43	3.87
Citric acid, %	0.78	8.22	2.98	1.03
Oxalic acid, %	0.81	3.04	2.79	3.16
Volatile oils, %	0.148	0.141	0.140	0.248
Alcohol-soluble resins, %	9.08	9.27	8.94	11.28
Reducing sugars as dextrose, %	22.09	0.21	0.21	12.39
Pectin as calcium pectate, %	6.19	9.91	12.14	6.77
Crude fiber, %	7.88	9.29	21.79	6.63
Ash, %	10.81	24.53	21.98	14.78
Calcium as CaO, %	2.22	8.01	4.79	4.22
Potassium as K_2O, %	2.47	5.22	4.40	2.33
Magnesium as MgO, %	0.36	1.29	1.03	0.69
Chlorine as Cl, %	0.84	0.71	0.26	0.69
Phosphorus as P_2O_5, %	0.51	0.57	0.53	0.47
Sulfur as SO_4, %	1.23	1.98	3.34	1.40
Alkalinity of water-sol. ash[b]	15.9	36.2	36.9	22.5

[a] Blend of Macedonia, Smyrna, and Samsun types.
[b] Ml. of 1 *N* acid per 100 g. tobacco.

Large variations occur within each individual type not only from farm to farm, but from year to year. Seasons of insufficient rainfall produce crops that are high in nicotine and total nitrogen. Variations appear in leaf composition among types of flue-cured, depending on the area in which they are grown. Type 11, grown in the heavier soil of the Piedmont area, usually contains more nitrogen and less carbohydrates than Type 13 grown in the lighter soil of South Carolina.

The dark air-cured types are coarser, gummier, and stronger than Burley and are characterized by a high nitrogen content, especially the nicotine fraction. Cigar types are generally characterized by a high nitrogen and mineral content and a low carbo-

hydrate level. Citric acid is the predominant nonvolatile organic acid and asparagine is generally the predominant amide. Analyses of various cigar types are shown in Table V.

TABLE V. Representative Analyses of Cigar Tobaccos.

(Leaf web after fermentation, moisture-free basis.)

Component	Connecticut shade-grown wrapper, type 61	Northern Wisconsin binder, type 55	Pennsylvania filler, type 41	Puerto Rican filler, type 46	Cuban filler, type 81	Sumatra wrapper, type 82
Total volatile bases as ammonia, %	1.233	1.055	0.874	0.707	1.478	0.670
Nicotine, %	1.47	2.68	2.04	0.90	2.23	1.42
Ammonia, %	0.914	0.575	0.495	0.348	1.012	0.313
Total amide as ammonia, %	0.225	0.199	0.165	0.264	0.232	0.208
Protein nitrogen as ammonia, %	2.20	2.14	2.88	3.26	2.81	3.01
Total nitrogen as ammonia, %	5.78	4.75	5.16	4.65	5.83	5.17
pH	6.27	6.33	6.10	7.21	6.56	7.25
Ash, %	23.79	24.94	21.50	22.45	22.57	22.34
Alkalinity of water-soluble ash[a]	90.4	45.5	47.0	62.7	43.0	93.6

[a] Ml. of 1 *N* acid per 100 g. tobacco.

Tobacco Grades

The tobacco plant produces leaves of distinctly different appearance and character, depending upon their position on the stalk. The lower leaves of the plant are "luggy" and the upper leaves are "leafy." Differentiation within these groups varies in degree, depending upon the type. Also the nomenclature varies with type. In flue-cured, the farm grades are known as *trash* or *primings*, *lugs*, *leaf*, and *tips* (6). With ascending stalk position, Burley falls into *flyings*, *trashes*, *lugs*, *bright leaf*, *red leaf*, and *tips* (24). The distribution of these grades may be markedly influenced by the weather and cultivation practices (6).

The center of the flue-cured plant produces leaf which is generally lighter in color and more hygroscopic. The sugar content is normally higher, whereas total nitrogen and nonvolatile organic acids are normally lower in the center leaves. The nicotine content is generally higher in the upper portion of the plant. The pH and mineral content decrease with successive pullings, potassium being more uniformly distributed than the other mineral components. The chlorine content diminishes sharply with successive pullings through the leaf grades. The lower leaves of air-cured types are normally lighter in color and more porous. The upper leaves are characteristically darker in color, heavier in body or density, and contain more gum. With ascending stalk position the leaf contains a lower proportion of mineral constituents, other than potassium, and a higher proportion of soluble nitrogenous components (24). The nicotine content attains a maximum in the leaf grades. The pH and alcohol-soluble resin content are highest in the lower portion of the plant. The oxalic acid content is least in the approximate center of the plant. In general, the upper leaves of the tobacco plant are the most aromatic, but only in Turkish does this pattern include the topmost leaves.

The fundamental factors entering into quality of tobacco for specific purposes are numerous. Each such factor occurs in a wide range of gradations, with the net result that the number of combinations of such factors is almost limitless. Each manufac-

turer has an established system of grades, the specifications for which are usually not coded, but which are, nevertheless, highly standardized. The nature of the product will dictate the farm grade from which the tobacco must be derived. Within the basic farm grades, the tobacco buyers compete for the highest quality leaf. Long training enables them to interpret observable characteristics such as color, body, conformation, texture, elasticity, aroma, and soundness in terms of desirability for a specific use. In recent years, the Federal Government has developed an elaborate system of grades, based on stalk position, quality, and color. These grades serve as the basis for price reporting and price support operations. Most manufactured products are blends of definite proportions of several grades. The process of blending of grades, types, and crops has attained a high state of development in the manufacture of popular brands of American cigarets.

Evaluation of Quality by Chemical Methods

Laboratory tests, including both chemical analyses and physical measurements, are now widely used to supplement empirical methods for the estimation of tobacco quality. Chemical analyses of leaf stock for the control of blends had its beginning about 1933. The measurement and codification of quality factors is the subject of continuing research by manufacturers and agricultural experiment stations. The quality of the tobacco is the most important factor in determining the taste quality of the finished product.

The percentage of nicotine, and the portion which it comprises of the volatile base fraction, has important effects on taste quality of smoking products. The combustion characteristics are important in determining the composition and palatability of the smoke. It is desirable that tobacco burn slowly and completely. Potassium favors the fire-holding capacity. Chlorine, sulfur, and reduced nitrogen are unfavorable. The percentage of reducing sugars in flue-cured and Turkish tobaccos is generally correlative with desirability for cigaret use, although at very high levels of sugar flue-cured has a smooth texture, dense leaf structure, and poor fire-holding capacity and aroma, with resultant impairment of the taste quality. The volatile oils of tobacco are the principal aromatic fraction, the total quantity of oil being less important than its composition. The alcohol-soluble resins of tobacco are desirable for their flavor and their palliative effect in smoking products. There does not appear to be any natural constituent of tobacco which is wholly undesirable, and for most components there are maxima above which the suitability for a given product is lessened. The practice of blending, which combines art and science, depends upon the balancing of the nitrogenous, carbohydrate, mineral, and aromatic components in the product.

In spite of great progress, there is much to be learned about the components of tobacco, especially the proteins, polyphenols, and essential oils. The interrelationship of physical and chemical characteristics of tobacco and manufacturing operations, as related to the nature of the smoke, is a subject of continuing study. Improved methods of analysis, with refined techniques for measuring the palatability of smoke, have contributed greatly to evaluation of technological improvements.

Curing and Marketing

The harvested tobacco is cured in preparation for market, usually in specially constructed curing barns.

The methods employed are classified, generally, as air-, flue-, fire-, and sun-curing.

Air-curing is normally conducted in large barns provided with free circulation of air. This method is employed for Burley, Maryland, dark air-cured, and cigar types. With the exception of cigar wrappers, Georgia-Florida sungrown binders, and, to a small extent, Burley, air-cured tobaccos are harvested by cutting the whole plant. The leaves are cured while still attached to the stalk. The success of the operation depends upon the control of relative humidity. This is accomplished by the use of side ventilators and, occasionally, exhaust fans. Further control may be obtained by open fires on the floor of the barn, a practice which has become general for cigar wrappers. The air-curing process usually lasts about four to six weeks.

For **flue-curing** the barns are small, tightly constructed, and are provided with a system of metal pipes by means of which artificial heat may be freely applied without allowing smoke to come into contact with the tobacco. A variation of this procedure involves the use of smokeless fuel and open-flame burners. The leaves are detached, or primed, and strung on laths, before curing. The heat is usually started at 90–100°F. and is raised by stages up to 170–180°F. The process requires three to five days for completion.

The temperatures employed in **fire-curing** are intermediate between flue-curing and air-curing. The process involves the application of copious quantities of hardwood smoke directly to the tobacco, which imparts characteristic odor and sheen.

Sun-curing is a modified form of air-curing employed in Eastern countries and for domestic aromatic types. The primed leaves, threaded and strung on racks, are exposed to the sunlight; the intensity of the sunlight may be increased by reflectant materials. In humid regions the tobacco is placed under cover at night and at other times, as needed, to protect it from rain. The sun-curing process requires several weeks for completion.

The process of curing fixes the color of the tobacco, imparts finish, and contributes to its aromatic qualities. Much has been published regarding the curing of different types of tobacco and the chemical and physical changes occurring during the various processes (2,7,10,14,17,18,33,34).

The harvested tobacco leaf, when ready for the curing barn, contains approximately 85% of water, the greater portion of which is lost during curing. The leaf is subjected to a period of starvation and gradually dies as the energy stored during ripening is consumed or becomes nonavailable. Respiration, translocation of constituents, and considerable chemical transformation occur. The chemical changes, the bulk of which take place during the yellowing period, appear to be principally oxidative and hydrolytic in nature. A notable loss of dry weight results, the extent of which is dependent upon the type of tobacco, and the curing method employed. The loss may vary from 5 to 10% for flue-cured to as much as 30% for air-cured types.

Leaf pigmentation, consisting of the plastid pigments chlorophyll, carotene, and xanthophyll, and the flavone-like phenolic pigments, undergoes drastic changes in passing from the intense green of fresh tissue to the various shades of yellow and brown of the cured product. The yellow color produced in the tobacco leaf during the yellowing stage of curing, following the degradation of chlorophyll, is due to the presence of carotene and xanthophyll, previously masked by the chlorophyll. These pigments decrease as curing progresses. The final coloration of the cured product is the result of the formation of complex condensation and polymerization products,

presumably of the melanoidin and tannin types, involving the reactions of polyphenols, carbohydrates, amino acids, and proteins.

The chemical and physical changes taking place in the stalk-curing of Burley tobacco and other air-cured types are much more extensive than in flue-cured. There is considerable translocation of soluble constituents from leaf to stalk under these conditions. The proteins are hydrolyzed with a resultant increase in water-soluble nitrogen compounds. Ammonia increases considerably, presumably because of oxidative deamination of amino acids. A substantial portion of the malic acid is converted to citric acid. The cured leaf is practically devoid of sugars and starch. The activities of the metabolic processes are considerably more extensive in stalk-curing than in the curing of detached leaves (38). The latter results in higher nitrogen content and the conversion of malic acid to citric acid is less complete. The curing of cigar tobaccos, and other air-cured types follows this same general pattern.

The oxidation of carbohydrates by respiration is inhibited on flue-curing as a result of the alteration of the cellular protoplasm and the inhibition of enzymic activity. Thus, the carbohydrates are "fixed." Sucrose is prominent among the sugars of freshly cured leaf. This is almost wholly inverted during storage before marketing. Starch, which forms a major component of the green tissue, is almost wholly hydrolyzed on curing.

After the grower has completed the curing of his tobacco, it is sold to manufacturers or processors. About 1.5 billion pounds of tobacco, including most of the non-cigar types, is sold annually at loose-leaf auction markets. About 10% of Maryland tobacco is still sold at the only surviving hogshead market, by sealed bids based on examination of samples from hogsheads. Cigar filler and binder tobacco, and minor amounts of dark types such as Kentucky and Tennessee fire-cured, are sold at the farm to buyers. Cigar wrappers are usually grown by dealers or manufacturers, or by private growers under contract.

Preparation for Aging and Storage

Domestic Cigaret Tobaccos. As purchased at the auction warehouse, flue-cured tobacco, and to a lesser extent, other types are a perishable commodity. The moisture content varies from basket to basket, but most of the tobacco contains so much moisture that it will mold and "sour" within a few weeks, if not processed. In the industry, tobacco at this stage is called "green," a term which has no reference to color but rather to the age and condition of the tobacco. At this stage it is unfit for use in manufacture, but must first be aged. Thinner, milder grades may require only one year, while heavier grades may require three years.

The first processing given green tobacco is its preparation and packing for aging. This is done in either of two ways, both of which result in uniform adjustment of the moisture content at about 10–12%. The older method is known as "redrying." A typical redrying machine is 14 ft. wide and 150 ft. long and is divided into five sections, in which different conditions are imposed. The first three of these are drying sections, each having a sharp increase in temperature up to the third, in which a temperature of as much as 212°F. is maintained. The fourth compartment is a cooling chamber, through which fans draw fresh air to cool the tobacco. At this point the tobacco is very dry and brittle, but in the fifth and last compartment it passes through an atmosphere humidified by steam and water sprays, which may be adjusted in such a manner

that the desired amount of moisture is added uniformly to the leaf. While still warm, the tobacco is packed in hogsheads with the aid of a hydraulic press. The hogsheads will contain 800–1000 lb. each. They are constructed of thin wooden staves and the usual construction permits exchange of air.

The other method of processing green tobacco which has come into prominence in recent years, is known as "green-stemming." The removal of the fibrous midrib of the leaf is called "stemming," which may be accomplished either before or after aging. Thus, green-stemming refers to stemming before aging. First, the tobacco must be "ordered," made soft and pliable by addition of a controlled amount of moisture. This is done by conveying the leaf through a long tunnel-like machine equipped with steam and water sprays, from which the tobacco emerges in a warm, pliable condition. After the stems are removed, the tobacco is passed through a "strip" dryer, which reduces the moisture content to the desired level for aging. The packed hogsheads, containing redried and green-stemmed tobacco, are then racked in storage warehouses for aging. These storages vary greatly in construction. Some have louvered sides, permitting almost unimpeded ventilation, while others are completely closed. The primary requirement is that the tobacco must not be subjected to excessively moist, stagnant air for protracted periods.

Imported Cigaret Tobacco. Oriental, or Turkish type, tobacco is packed in small bales, weighing about 150 lb. or less, and covered with closely woven burlap.

Turkish type tobacco is not normally redried or otherwise subjected to high temperatures, nor is it stemmed. Stored in dry, closed buildings for aging, the bales are stacked 5 or 6 high on platforms about 8 in. above the floor, permitting ample circulation of air beneath. During the warm months of the year, new or green tobacco undergoes active "sweating," which becomes less active with age. While sweating is in progress, the tobacco absorbs moisture from the atmosphere and the bales swell, with an accompanying increase in temperature. Because of these factors, actively sweating bales must be turned and their positions in the stack changed at least once a month, the top bales going to the bottom.

Other Types. The handling of cigar tobaccos differs greatly from the processing given cigaret tobaccos. They are not normally stemmed until fermentation and aging are complete. Variations from the above procedures occur, also, in some of the manufacturing and export types of tobacco, such as dark air-cured and fire-cured. In these types, the tobacco is sometimes hung for air-drying instead of being machine-dried. Packing is accomplished with higher moisture content as a rule than that employed for cigaret types. In all export types there may be variation in moisture content on packing, depending on the country of destination.

Aging and Fermentation

AGING OF CIGARET TOBACCOS

Unaged tobaccos will either possess a flat, straw-like aroma or have a sharp, unpleasant odor characteristic of freshly dried plant material. They yield a pungent, irritating smoke with a harsh and bitter flavor. In order to produce a product with a pleasing aroma, and which gives a mild and flavorful smoke, these tobaccos must be subjected to further manipulation. For cigaret tobaccos, flue-cured, Burley, Turkish, and Maryland, this process is called "aging."

The improvement in smoking quality on aging is the result of numerous chemical

changes taking place, which, for the most part, remain to be elucidated. It results from the elaboration of aromatic components and loss or fixing of the irritating components. The improvement in aroma and other manifestations of the aging process are at the present time best evaluated by means of sensory perception.

On aging, cigaret tobaccos slowly undergo a darkening in color and a loss in brightness. This is most noticeable in flue-cured and Turkish types. Unaged tobaccos frequently have some residual green color due to incomplete conversion of chlorophyll during the curing process. This is usually lessened or lost during aging, resulting in a more uniform color in the leaf.

Very little of an analytical nature has been published concerning the changes occurring during the aging of cigaret tobaccos. The most extensive study has been that of Dixon and co-workers (9), who reported on the aging of bright tobacco over a thirty-month period. Darkis and Hackney (7) reported changes resulting from the aging of Turkish tobacco of the Smyrna type.

The most characteristic chemical changes occurring during the aging of flue-cured, Burley, and Turkish tobaccos are an increase in volatile acids, including formic, and decreases in α-amino nitrogen and pH. Flue-cured and Turkish also show a loss of reducing sugars and volatile bases other than nicotine.

Flue-cured tobacco packed at 11% moisture and aged for 2 years will usually increase 10–20% in moisture content. Burley tobacco aged under the same conditions shows an increase of 3–8% moisture. Turkish tobacco packed at a moisture content above 13% will normally decrease in moisture on aging.

Dixon and co-workers (9) reported a loss in nicotine of 10.95% in flue-cured tobacco aged for 30 months. Available data on the aging of cigaret tobaccos show the nicotine loss to be usually in the range of 1–5%. Loss in dry weight of cigaret tobaccos on aging is usually less than 1%.

Flue-cured and Burley tobaccos, upon storing for 30 to 60 days in an atmosphere of 65–80% r.h. and 90–110°F., exhibit the desirable changes in aroma and smoking quality which result from about one year of natural aging. This process of forced or accelerated aging is being used to some extent in the cigaret industry.

There is a disagreement among workers in the field as to the mechanism of tobacco aging. The process is variously attributed to: (*1*) changes that result from purely chemical reactions among the leaf constituents; (*2*) changes that occur primarily due to the presence of microorganisms in tobacco; and (*3*) changes resulting from action of enzymes native to the plant tissue. Frankenburg (11) discussed the disagreements among the various authors as to the importance of these mechanisms. The presence of both microorganisms and enzymes in unaged cigaret tobaccos has been reported.

FERMENTATION OF CIGAR TOBACCOS

There are two techniques of cigar leaf fermentation in general use, the bulk sweat and the case sweat. The bulk sweat, the older of the two processes, is employed for all shade-grown cigar wrappers, the Florida sun-grown cigar filler and Florida binder leaf, fire-cured leaf for Italian cheroots, and most of the filler leaf for short-filler cigars.

Preparatory to forming the bulk, moisture is added by means of a water spray. The moisture content varies widely among types, grades, crops, and manufacturers. It is typically about 20–25% for wrappers and 30–40% for binders and fillers. Large piles or bulks of the moistened leaves are assembled to ferment or sweat. Bulks of

cigar wrappers may contain 4,000 lb. or less of tobacco; they are allowed to ferment until a temperature of 115–120°F. is reached. For binders and fillers the bulks may contain 20,000–40,000 lb., and may be allowed to reach a temperature of 130°F., or even 150°F. Upon reaching these maximum temperatures the bulks are taken apart and rebuilt. As an attendant operation the hands are shaken out to replace the gaseous products of fermentation with fresh air. About 5 or 6 bulkings are usually necessary for complete fermentation.

For filler types the bulk sweat has been largely replaced by the case sweat. About 250–400 lb. of leaf are packed into wooden cases and pressure is applied. These cases are assembled in large blocks in warehouses for the first phase of fermentation known as the natural sweat. Cigar binders may be given a preliminary bulk fermentation, or they may be naturally sweated in cases for several years prior to a more vigorous case sweat.

At the end of the natural sweat, which requires one year or more, filler tobacco, and some binder tobacco, is subjected to an additional treatment called the resweat. For this operation the leaves are submerged in water to absorb the desired amount of moisture. They are then repacked in cases under pressure and stored at about 110–115°F., and about 60% r.h. This storage may be periodically interrupted by repacking and airing the leaves whenever the spontaneous heat of the tobacco has reached its peak. The number of these heats varies with the crop undergoing fermentation. Variations in resweating procedure may include a period of 1–2 weeks forced sweat in rooms maintained at 130–150°F., or a combination of "mulling" at about 80°F. and forced sweat. The mulling operation is a variation of the bulk sweat in which a smaller mass of tobacco is used. The tobacco, at elevated moisture content, is stored in rooms maintained at about 80°F. The various fermentation procedures have been described very fully in the literature (11,14,33).

Cigar tobacco leaves, on fermentation, show characteristic changes in odor, color, and texture. Initially, they have a pungent raw smell that gradually gives way to an aromatic, partly ammoniacal aroma. Darker shades of brown develop which lack the glossy luster of the unfermented leaves. The gummy surface layer disappears and the leaf acquires a velvety texture. The entire leaf becomes more tender and increasingly brittle. There is loss in dry weight which may vary from about 5% for wrappers up to 10–12% or more for fillers. The fire-holding capacity is usually increased and the moisture-holding capacity usually diminished.

These changes are accompanied by generation of heat, absorption of oxygen, and evolution of carbon dioxide, ammonia, and methyl alcohol. Small quantities of essential oils, volatile acids, and carbon monoxide have also been found among the vapors in fermentation chambers.

The nicotine content is normally reduced from 20 to 50% on fermentation. Only a small portion of this reduction may be ascribed to volatilization. Frankenburg and Gottscho (12) reported the results of experiments in which 82% of the nicotine was removed. The products of nicotine breakdown were identified and evaluated as follows: 20 parts oxynicotine, 3 parts of a mixture of 2,3'-bipyridine and methyl 3-pyridyl ketone, 15 parts nicotinic acid, 30 parts water-insoluble pyridine derivatives, 7 parts unidentified chloroform-soluble oxidation products, 18 parts unchanged nicotine, and 7 parts unrecoverable as pyridine nitrogen.

Large amounts of ammonia are produced during fermentation. The amide nitrogen decreases by about the same amount. During active fermentation the pH

increases, presumably as a result of elimination of organic acids by total oxidation and decarboxylation. The final pH may be greater or less than the original, depending on the sequence of manipulations. The total nitrogen decreases slightly. The insoluble nitrogen increases. α-Amino nitrogen is sharply reduced. Evidence has been presented which indicates that a portion of the α-amino nitrogen undergoes oxidative deamination with the formation of ammonia and another portion forms insoluble condensation products with polyphenolic substances. The pectin methyl alcohol, polyphenols, total resins, waxes, volatile oils, pectin, and total nonvolatile acids decrease. The volatile acids increase sharply.

The mechanism and causative agents of tobacco fermentation have been studied since 1858 (11) and various theories have been advanced. The process has been said to be caused by the enzymes of the leaf, by bacteria, by fungi, and by chemical changes occurring without the aid of either microorganisms or enzymes. The early workers subscribed, generally, to the bacterial theory. In a series of papers published from 1899 to 1901, Loew (23) showed the presence of an oxidase, a peroxidase, and catalase in the leaf tissues in green as well as in dried and fermented tobacco leaves. The later experiments of Neuberg and Kobel (25) lent support to the enzymic theory. In 1934, Johnson (21), as a result of a thorough study of fermentation of cigar tobacco, concluded that microorganisms, specifically fungi, may play a role in addition to the leaf enzymes in the fermentation, although these organisms do not necessarily appear to be essential to the process.

More recently, Jensen and Parmele (20) found bacteria to be the agents which initiate the fermentation process in bulks of cigar leaf tobaccos. They found that the enzymes appearing in the fermenting leaves are of bacterial, rather than of plant origin, and that the enzymes are capable of producing a steady rise in bulk temperature after the numbers of bacterial cells have started to decrease. Frankenburg and Gottscho (12) reported that nonenzymic heat-stable catalysts are capable of promoting the fermentation of Pennsylvania tobacco to a considerable extent.

INSECT PESTS OF STORED TOBACCO

Tobacco in storage is subject to the attack of the cigaret beetle (*Lasioderma serricorne* F.) and the tobacco moth (*Ephestia elutella* Hbn.).

The adult cigaret beetle is mahogany brown and less than 1/8 in. long. The larva is a hairy grub which may feed on any type of tobacco or tobacco product, although Burley and dark fire-cured tobaccos are seldom attacked to any appreciable extent.

The adult tobacco moth is gray and measures about 3/8 in. from head to tips of the folded wings. The larva, a pink caterpillar, infests flue-cured and Turkish type tobaccos. The heaviest attack is in the grades which are high in sugar and low in nicotine.

In storages where it is not feasible to seal all openings, the dispersal of contact insecticides in the form of mists or fogs is the only known method of control. The most commonly used insecticide is a mixture of pyrethrin resins (pyrethrum extract) in deodorized kerosene. It is directed at the adult, or flying stage, of each insect with the object of destroying them before their eggs are deposited. Fumigation at atmospheric pressure may be used successfully if the storage buildings can be closed and tightly sealed. For this purpose hydrogen cyanide gas and methyl bromide are effective. A considerable amount of tobacco is fumigated in vacuum chambers. When properly conducted this process destroys all insect life. In addition to hydrogen cyan-

ide and methyl bromide, a mixture of ethylene oxide and carbon dioxide or a mixture of acrylonitrile and carbon tetrachloride may be used as fumigants.

Manufacture

Cigarets. The wide variations in composition of tobacco due to type characteristics, growing season, stalk position, and those peculiar to the individual grower and farm, necessitate an elaborate system of blending. The initial blending takes place at the redrying plant, or green stemmery, where the tobaccos from 25 to 50 hogsheads, representing all markets of a given belt, are loaded onto a moving conveyor. On packing for storage, samples of each grade are drawn at regular intervals for analysis and determination of moisture. After aging, and stemming in the case of redried leaf, the moistened strips are blended and thoroughly mixed in rotating drums. Tobacco from a large number of hogsheads is worked simultaneously at this stage. All grades and belts within a type, and usually three crop years, are represented, the formulation being governed by the analysis of the leaf stock. Blends of each of the 4 types are prepared and the types are later blended. The Burley and Maryland are usually intermixed and later converge with a blend of flue-cured and Turkish to form the complete blend which is subjected to further mixing operations both before and after shredding. The process may include a bulking operation which permits interchange of soluble constituents.

The proportions of the types and belts represented in the blend are closely guarded trade secrets. Flue-cured may constitute 45–75% of the blend; Burley, 15–45%; Turkish, 5–13%; and Maryland, 1–5% (7). Some manufacturers include small quantities of other types such as Latakia. The basic formula has a determining effect on taste characteristics and is not normally varied.

The blend of Burley and Maryland strips may be subjected to a "casing" operation, which consists of immersion in a warm aqueous suspension and subsequent wringing. The added solids, which may be 15–25% of the tobacco weight, usually consist principally of invert sugar, with licorice, chocolate, cocoa, a humectant, and other ingredients in lesser quantities. Variations of this procedure may include the spraying of one or more of these materials onto the Burley-Maryland blend or onto the complete blend before shredding. An alcoholic solution of essential oils may be applied to the blend after shredding.

The addition of sugar to those types that are lacking in natural sugar contributes to the homogeneity of the blend and results in improved smoking quality. Chocolate and cocoa contribute flavor and a perceptible smoothing effect on the smoke. The humectants increase the pliability as well as the moisture-holding capacity. They may be added in amounts ranging from 2 to 4%. Glycerin is the most widely used hygroscopic agent. Diethylene glycol, triethylene glycol, propylene glycol, and sorbitol are used to some extent.

Tobacco, in processing, undergoes a sequence of drying and moistening operations which are necessary to permit stemming, sizing, cleaning, and shredding. The conditions of drying may exert important effects on the physical and chemical nature of the tobacco. The fluffiness and pliability of the finished tobacco have important effects on the physical characteristics of the cigaret. Improper drying will result in a brittle, inelastic product. Drying operations are designed to maintain the desirable flavor and physical qualities of the tobacco while disposing of volatile irritating sub-

stances. Specialized drying processes for tobacco have been the subject of several patents (40–42).

The control of moisture is a major problem in cigaret manufacture. Vacuum steam chambers are generally employed for moistening tobacco in hogsheads. Steam-water sprays are generally employed at later stages. Conditioned atmospheres are necessary at various stages of manufacture; the requirements for cut storage and fabrication are especially critical for effective control of moisture. Electrical methods for rapid measurement of moisture are widely used.

The fabrication and packaging of cigarets are primarily mechanical operations, but exact specifications, as well as accurate knowledge of composition of the materials, other than tobacco, are required. The cigaret paper is composed of carefully refined flax fiber to which about 20–25% calcium carbonate is added as a filler to regulate the burning characteristics and increase opacity. The paper is generally sealed with casein or starch adhesives. The cellophane wrapper for the cigaret package is usually sealed with a glycol ether. Since tobacco is particularly susceptible to contamination by foreign odors, great vigilance must be exercised over the atmosphere of fabrication areas and over the packaging materials.

Cigars. The manufacture of cigars is next to cigarets in importance to the tobacco industry, and is a much older enterprise. However, while cigaret production continued to increase through 1952, cigar production reached a maximum in 1930.

Almost all cigars are produced today by semi-automatic machines, only a few of the most expensive brands being hand-made in the original manner.

Cigars are made in a wide variety of shapes and sizes, but nearly all consist of three essential components: filler, binder, and wrapper. The pieces of tobacco forming the filler or core of the cigar may vary in size and length from leaf-size or "long filler," used in the more expensive brands, to relative short "scrap" fillers used in the least expensive brands. The more expensive cigars are usually composed entirely of Cuban tobacco and are described as "Clear Havana," while those of moderate price may consist of Cuban and domestic, Puerto Rican and domestic, or a combination of all three. The lower-priced cigars usually contain a scrap filler which is composed of several types of tobacco, blended in the manner of a cigaret.

Whatever the combination of filler, binder, and wrapper, the selection of components that will produce a harmonious blend, and result in the desired flavor and burning characteristics, is a highly developed art.

The manufacturing process consists, essentially, of forming the filler into the general shape of a cigar, wrapping it with the binder, and molding it more closely to proper shape. The precut wrapper is next applied, being wound spirally around the cigar and always with the veins running parallel to the axis of the cigar. The tip is sealed with a paste usually composed of gum tragacanth and sodium borate or other mold inhibitor.

The freshly made cigars are placed in racks for shaping and adjustment of moisture.

Before packaging, the cigars are carefully examined for imperfections and graded as to color so that the cigars in any one box have a similar shade. Color classifications are finely drawn. In the U.S. the five classifications in general use are:

Claro:	lightest shade
Colorado-Claro:	light medium
Colorado:	medium
Colorado-Maduro:	dark medium
Maduro:	dark

The individual cigars are usually enclosed in moistureproof cellophane, which is the final step before packing in boxes.

Smoking (Pipe) Tobacco. The principal types used in the manufacture of smoking tobacco are Burley, Green River, One Sucker, and flue-cured. Perique and Latakia are also used, especially in "high-grade" mixtures. Among these, Burley is by far the most important from the standpoint of poundage. The grades employed are heavier-bodied, more leafy, and higher in nicotine than those used for cigarets. The same blending principles employed in cigaret manufacture apply.

Smoking tobacco is usually more heavily cased than cigaret tobaccos, the added solids ranging from 20 to 35%. In addition to sugar, a large variety of other materials, such as licorice, humectants, chocolate, cocoa, various spices, and essential oils, may be added.

Smoking tobacco is prepared in a variety of forms such as plug-, long-, fine-, cube-cuts, and granulated, or combinations of these.

Chewing Tobacco and Snuff. Sun-cured, Burley, One Sucker, Green River, flue-cured, fire-cured, and cigar leaf scrap are among the types used in the manufacture of chewing tobaccos. In general, all chewing tobaccos are heavily cased and flavored. Saccharin is used to a limited extent in some chewing tobaccos as a sweetening agent. Among the various forms of chewing tobacco, plug, twist, fine-cut, and scrap are the best known. Plug is the predominant form. Some of these forms are also used for smoking just as some tobaccos produced chiefly for smoking are also suitable for chewing.

Snuff is made from fire-cured and dark air-cured types. The leaf is usually cut into strips 1–2 in. wide and subjected to a very severe fermentation. It is then dried and reduced to a powder. Most snuff products contain a considerable quantity of added flavors (14).

Tobacco By-Products

Almost every operation in the manufacture of tobacco products produces some waste material, of which stems, dust, and siftings from cleaning operations form the bulk. The utilization of this waste material, which may comprise 25% or more of the original leaf weight, and the utilization of very low grade and damaged tobacco, is of considerable economic importance.

At the present time, nicotine, normally in the form of the sulfate, is the most important by-product derived from tobacco. It has been widely used as an insecticide, particularly as a contact poison for soft-bodied sucking insects; however the synthetic organic phosphates have partially supplanted it in recent years. Nicotine may be recovered from tobacco by steam distillation of the ground waste, to which an alkaline aqueous solution has been added. The distillate is usually collected in sulfuric acid. Extraction with organic solvents is also practiced, the nicotine being extracted from the solvent by sulfuric acid. The nicotine sulfate, obtained by either method is usually concentrated and marketed as a 40% solution.

In the production of nicotine sulfate, some ammonia is usually recovered. It is converted to the sulfate and is usable in fertilizers. The tobacco residue from the extraction process contains an appreciable amount of potassium, as well as some nitrogen and phosphorus. After drying, it finds use as a valuable conditioner for commercial fertilizers.

Tobacco stems are widely used in foreign countries and to a lesser extent in the U.S. for reincorporation in cigaret and smoking tobacco blends. For this purpose the stems, after removal, are rolled to a thickness approximately the width of the shreds and then cut to a width approximating the thickness of a cured leaf. Processes have been developed for reconstitution of ground tobacco into a sheet for use in smoking products (45,46), for the production of nicotinic acid from tobacco waste (44), and for the extraction of rutin (43). Extracts of tobacco stems and waste have been used to a limited extent for flavoring low-grade tobaccos, particularly in Germany. The use of tobacco waste for the manufacture of an insulating board (39) and for the recovery of organic acids and pectin has been investigated but has not come into commercial use.

Nature of Tobacco Smoke

Tobacco smoke is an aerosol consisting of millions of semiliquid particles per cubic centimeter of gaseous phase. The diameter of these particles varies from about 0.1 micron to considerably over 1 micron with a preponderance in the 0.3–0.7-micron range. Upon smoking by the procedure described by Bradford and co-workers (4), the particulate phase from a typical domestic blended cigaret weighs approximately 40 mg. while the gaseous phase weighs about ten times this amount. Of the latter, 15–20 mg. is carbon monoxide and 50–90 mg. is carbon dioxide. Nitrogen and oxygen from the air are the principal gases present.

Divergent results have appeared in the literature concerning the quantitative composition of cigaret smoke, due to differences in conditions of smoking. For example, Pyriki (26) attributed his failure to check the findings of Wenusch (35) to differences in technique of smoking or in the method for assaying the nicotine. The effects of variations in technique on the amount of nicotine transferred to the smoke have been shown by Jensen and Haley (19). The mechanical smoking machine described by Bradford, Harlan, and Hanmer (4), which simulates human smoking in a reproducible manner, has done much to extend the information on smoke composition.

TABLE VI. Composition of Cigaret Smoke.

(In milligrams/liter.)

Components	Flue-cured	Burley	Maryland	Turkish	Blend
Volatile bases as ammonia	1.13	2.29	1.69	1.02	1.55
Nicotine	6.42	9.08	5.44	3.16	7.14
Volatile bases other than nicotine as ammonia	0.46	1.34	1.12	0.69	0.80
Volatile acids as acetic	6.19	5.33	6.44	5.10	5.93
Formic acid	1.30	1.13	1.44	0.80	1.20
Ratio: volatile acids[a]/volatile bases	1.55	0.66	1.08	1.42	1.09
Volatile aldehydes as acetaldehyde	5.31	17.28	8.00	3.65	7.43
Resins	47.1	54.8	62.7	45.0	55.3

[a] In equivalents.

The tobacco from which smoke is derived is the most important factor influencing its composition. Characteristic differences in composition of the smoke from the four principal cigaret types are shown in Table VI.

Nicotine and ammonia are the principal bases found in cigaret smoke, and acetic and formic acids are the principal volatile acids. Propionic, butyric, and valeric acids and traces of amines are also present.

The resin fraction consists of that material in the particulate phase which is soluble in chloroform and insoluble in dilute mineral acid. It includes components that are important from the standpoint of taste and palatability of the smoke. It also exerts an emollient action by serving to reduce the concentration of the more irritating smoke constituents. Twenty to twenty-five per cent of this fraction is a volatile, highly aromatic, yellowish brown oil. The remainder of the resins may be divided into acidic (about 20%), phenolic (about 10%), and neutral fractions.

Many other constituents of cigaret smoke have been reported by various investigators. Among these are the following, with amounts found in the smoke of a blended cigaret when smoking is carried out as previously described (in mg./liter): other alkaloids, trace; pyridine, 0.3; furfural, 0.36; methanol, 1.8; hygroscopic agent, 9.0; volatile oil, 7.5; phenol, 0.4; guaiacol, 0.05; *m*-cresol, 0.07; *o*-cresol, 0.08.

Because of its well-known pharmacological properties, nicotine has received more attention in the literature than any other constituent of tobacco smoke. It acts on the circulation by stimulating the autonomic nervous system. The effects on heart rate, blood pressure, and vasoconstriction are similar in degree to those produced by many other stimuli encountered during an active day. They are evanescent in character and subside within 10–30 minutes following cessation of smoking. Nicotine is quite rapidly detoxified in the body, and day-to-day accumulation does not occur. Quantitative studies have shown that virtually all of the nicotine and its metabolites are eliminated in the urine, about 10% being in the form of unchanged nicotine and the remainder as products of biotransformation.

Using the nicotine content of smoke as a basis, the following generalizations regarding the effects of arbitrarily changing smoking procedure may be made: (*1*) increasing the puff volume (from 25 to 45 ml.) decreases the concentration of nicotine in the smoke but increases materially the total amount obtained per cigaret; (*2*) changing the duration of puff (from 1.4 to 2.6 seconds) increases the concentration of nicotine in the smoke and increases slightly the amount obtained per cigaret; (*3*) increasing the puffing frequency from one puff per minute to two puffs per minute decreases the concentration of nicotine in the smoke but materially increases the amount obtained per cigaret; (*4*) increasing the butt length decreases the concentration of nicotine in the smoke and decreases the amount obtained per cigaret.

The physical characteristics of the cigaret also play an important part: (*1*) increasing the weight of the cigaret decreases the concentration of nicotine in the smoke but increases the amount obtained per cigaret; (*2*) increasing the moisture content of the cigaret decreases the concentration of nicotine in the smoke and decreases the amount obtained per cigaret.

The above considerations apply to "main stream" smoke—that which is drawn into the mouth by the smoker. "Side stream" smoke—that which is given off from the end of the burning cigaret, is quite different in character. Whereas main stream smoke is acid with a pH, depending upon the type or character of the blend, ranging from 4.5 to 6.3, side stream smoke is definitely alkaline, having a pH upwards of 9.0. The main stream smoke from cigars is about neutral. It should be pointed out that pH determinations are not reliable measures of the true character of smoke because of discrepancies resulting from the high carbon dioxide content, high buffer concentration,

and changes in composition of the smoke when various means are used to eliminate the effect of carbon dioxide. They should only be used as a guide to the general character of the smoke.

The alkalinity of the side stream smoke results from the more complete oxidation of the free burning tobacco with greater degradation of the combustion products. Ammonia is present in relatively high concentration.

The approximate distribution of the nicotine originally present in the tobacco burned, when smoked under the conditions described by Bradford, Harlan, and Hanmer (4) is: main stream 20%, side stream 40%, condensed in butt 6%, destroyed 34%.

Cigaret smokers are generally inhalers; pipe and cigar smokers inhale to a much lesser degree. Using a micromethod developed by Spies (27) for determination of nicotine, Hillsman (16) reported a retention of 60–96% of the nicotine in main stream smoke by inhalers, depending upon depth of inhalation, and somewhat less than 20% by noninhalers. The retention of resins was slightly less.

Recently filters and, more particularly, filter tips have become more popular. Haag, Finnegan and Larson (15) reported on the effect of filters on irritation by cigaret smoke and, more recently, Wollman (37) made determinations of the filtering efficiency of various commercial-type filter tips. The tips used were primarily mechanical filters made from various fibrous materials such as cellulose acetate, paper, cotton, α-cellulose, and asbestos. Varying degrees of efficiency were obtained, depending upon the tightness of the filter and the efficiency of the material. Tobacco itself serves as an excellent mechanical filter. The possibility of combining mechanical filters with specific adsorbents, particularly for the gaseous constituents of smoke, have been explored. Materials considered for this purpose include silica gel, active alumina, bentonite, and activated charcoal.

The foregoing discussion is primarily concerned with cigaret smoke. The same general concepts apply to cigar and pipe smoke although quantitative and qualitative differences in composition may occur.

An increasing interest in the question of the effect of tobacco on health may be expected to produce new knowledge through research being planned and conducted under the auspices of the tobacco industry and of various scientific organizations. Much work is in progress on the composition of smoke, using refined techniques for collection and handling. These investigations include studies of the physical characteristics of the aerosol, the degree of heterogenicity of the particles, the mechanism of formation of the aerosol, and further exploration of the components responsible for irritative effects. Studies of sites of deposition of the particulate phase, the speed of adsorption and elimination of the smoke by the smoker are part of a long-range plan, one purpose of which is to ascertain if smoking has any adverse affect on health.

Bibliography

(1) Anderson, P. J., *Conn. Agr. Exptl. Sta., Bull.*, **564** (1953).
(2) Bacon, W. W., Wenger, R., and Bullock, J. F., *U.S. Dept. Agr. Bull.*, **1032** (1951).
(3) Bennett, R. R., Hawks, S. N., Jr., and Garriss, H. R., *N. Carolina State Coll., Agr. Extension Service, Circ.*, **302** (rev. 1951).
(4) Bradford, J. A., Harlan, W. R., and Hanmer, H. R., *Ind. Eng. Chem.*, **28**, 836–39 (1936).
(5) Clayton, E. E., *Phytopathology*, **43**, 239–44 (1953).
(6) Darkis, F. R., Dixon, L. F., Wolf, F. A., and Gross, P. M., *Ind. Eng. Chem.*, **28**, 1214–23 (1936).

(7) Darkis, F. R., and Hackney, E. J., *Ind. Eng. Chem.*, **44**, 284–91 (1952).
(8) Darkis, F. R., Hackney, E. J., and Gross, P. M., *Ind. Eng. Chem.*, **39**, 1631–42 (1947).
(9) Dixon, L. F., Darkis, F. R., Wolf, F. A., Hall, J. A., Jones, E. P., and Gross, P. M., *Ind. Eng. Chem.*, **28**, 180–89 (1936).
(10) Frankenburg, W. G., "Chemical Changes in the Harvested Tobacco Leaf. Part I. Chemical and Enzymic Conversions during the Curing Process," in Nord, *Advances in Enzymology*, Interscience, N.Y., 1946, Vol. VI, pp. 309–87.
(11) Frankenburg, W. G., "Chemical Changes in the Harvested Tobacco Leaf. Part II. Chemical and Enzymic Conversions during Fermentation and Aging," in Nord (see ref. 10), 1950, Vol. X, pp. 325–441.
(12) Frankenburg, W. G., and Gottscho, A. M., *Ind. Eng. Chem.*, **44**, 301–5 (1952).
(13) Gage, C. E., *U.S. Dept. Agr., Agr. Marketing Admin., Circ.*, **249** (rev. 1942).
(14) Garner, W. W., *The Production of Tobacco*, rev. 1st ed., Blakiston, Philadelphia, 1951.
(15) Haag, H. B., Finnegan, J. K., and Larson, P. S., *Arch. Otolaryngol.*, **48**, 41–46 (1948).
(16) Hillsman, O. L., "The Retention of Nicotine by the Cigaret Smoker," paper presented before Tobacco Chemists Research Conference, The Pennsylvania State College, State College, Pennsylvania, 1950.
(17) Jeffrey, R. N., *Ky. Agr. Expt. Sta. Bull.*, **496** (1946).
(18) Jensen, C. O., *Ind. Eng. Chem.*, **44**, 306–9 (1952).
(19) Jensen, C. O., and Haley, D. E., *J. Agr. Research*, **51**, 267–75 (1935).
(20) Jensen, C. O., and Parmele, H. B., *Ind. Eng. Chem.*, **42**, 519–22 (1950).
(21) Johnson, J., *J. Agr. Research*, **49**, 137–60 (1934).
(22) Kinney, E. J., Price, W. A., Valleau, W. D., Karraker, P. E., Bortner, C. E., and Hunt, R. A., *Univ. Ky. Coll. Agr. Home Economics, Agr. Extension Service, Circ.*, **482** (1950).
(23) Loew, O., *U.S. Dept. Agr. Bull.*, **59** (1899); **65** (1900); **68** (1901).
(24) Moseley, J. M., Harlan, W. R., and Hanmer, H. R., *Ind. Eng. Chem.*, **43**, 2343–47 (1951).
(25) Neuburg, C., and Kobel, M., *Biochem. Z.*, **179**, 459–90 (1926); **190**, 232–40 (1927); **229**, 455–63 (1930); *Naturwissenschaften*, **23**, 800–1 (1935); *Enzymologia*, **1**, 177–82 (1936).
(26) Pyriki, C., *Chem.-Ztg.*, **58**, 279 (1934).
(27) Spies, J. R., *Ind. Eng. Chem., Anal. Ed.*, **9**, 46–47 (1937).
(28) Tenhet, J. N., and Bare, C. O., *U.S. Dept. Agr. Bull.*, **869** (1951).
(29) *U.S. Dept. Agr., Agr. Marketing Service, Statistical Bull.*, Annual Report on Tobacco Statistics, **138** (1953).
(30) *U.S. Dept. Agr., Foreign Agr. Service, Foreign Agr. Circ.*, **FT 1-54** (1954).
(31) *U.S. Dept. Agr., Agr. Marketing Service, Rept.* **TS-67** (1954).
(32) Valleau, W. D., *Econ. Botany*, **6**, 69–102 (1952).
(33) Vickery, H. B., and Meiss, A. N., *Conn. Agr. Expt. Sta., Bull.*, **569** (1953).
(34) Ward, G. M., *Can. Dept. Agr., Tech. Bull.*, **37** (1942).
(35) Wenusch, A., *Chem.-Ztg.*, **58**, 206–7 (1934).
(36) Westbrook, E. C., *Univ. Georgia Coll. Agr., Agr. Extension Service, Bull.*, **579** (1953).
(37) Wollman, W., *J. Am. Med. Assoc.*, **152**, 917–20 (1953).
(38) Wright, H. E., and Burton, W. W., "The Effects of Priming on the Chemical Changes That Occur During the Curing of Burley Tobacco," paper presented before Tobacco Chemists Research Conference, Bowman Gray School of Medicine of Wake Forest College, Winston-Salem, N.C., 1953.
(39) U.S. Pat. 1,756,722 (April 29, 1930), R. M. Hixon and R. B. Arnold (to Tobacco By-Products and Chemical Corp.).
(40) U.S. Pat. 1,880,336 (Oct. 4, 1932), A. Wenusch (to General-Direktion der Osterr. Tabakregie.).
(41) U.S. Pat. 2,124,012 (July 19, 1938), H. L. Smith (to Thermal Engineering Corp.).
(42) U.S. Pat. 2,309,975 (Feb. 2, 1943), J. M. Moseley and R. P. Hudson (to The American Tobacco Co.).
(43) U.S. Pat. 2,520,127 (Aug. 29, 1950), J. F. Couch, J. Naghski, and W. L. Porter (to United States of America as represented by Secretary of Agriculture).
(44) U.S. Pat. 2,586,808 (Feb. 26, 1952), W. G. Frankenburg (to General Cigar Co.).
(45) U.S. Pat. 2,592,553 (April 15, 1952), W. G. Frankenburg and P. W. Garbo (to General Cigar Co.).
(46) U.S. Pat. 2,592,554 (April 15, 1952), W. G. Frankenburg (to General Cigar Co.).

W. R. HARLAN AND J. M. MOSELEY

TOBIAS ACID, $H_2NC_{10}H_6SO_3H$. See *Naphthylamines and naphthylaminesulfonic acids*, Vol. **9**, p. 264.

TOCOPHEROLS. See *Food chemicals*, Vol. **6**, p. 839; *Vitamins* (*vitamin E*).

TOILET PREPARATIONS. See *Cosmetics*; *Perfumes*, Vol. **10**, p. 15; *Shampoos and other hair preparations*; *Soap*, Vol. **12**, p. 590; *Tints, hair dyes and bleaches.*

TOLIDINES, $(NH_2(CH_3)C_6H_3)_2$. See *Benzidine*, Vol. **2**, p. 453.

TOLU BALSAM. See *Emetics and expectorants*, Vol. **5**, p. 684; *Resins, natural*, Vol. **11**, p. 681.

TOLUENE

Toluene (toluol, methylbenzene), $C_6H_5CH_3$, formula weight 92.134, is a liquid hydrocarbon, the second member of the aromatic series beginning with benzene. Toluene is volatile and flammable. It is colorless, but more refractive than water. It has a characteristic odor like that of benzene, but milder and slightly resembling the odor of balsamic resins. It derives its name from balsam of Tolu (see Vol. **11**, p. 681). Toluene was discovered by Pelletier and Walter about 1835 in the products of dry distillation of natural resins containing esters of toluic acids.

The name toluene is approved by the International Union of Chemistry for the pure compound, but the commercial product is generally called toluol. Its chief industrial sources are petroleum and bituminous coal. Its principal uses in bulk are as the raw material for the explosive trinitrotoluene, as an industrial solvent, and as a constituent of gasoline. Other important uses are as the raw material for intermediate chemicals in making dyes, perfumes, and medicines. Typical intermediates made from toluene are benzoic acid, benzaldehyde, vinyltoluenes, and the toluidines.

Physical and Chemical Properties

CONSTANTS

F.p., −94.991°C.; b.p., 110.625°C.; rate of change of b.p. with pressure at b.p., 0.04630°C./mm. Hg; d_4^{20}, 0.86694; n_D^{20}, 1.49693; vapor pressure at 25°C., 28.3 mm. Hg; vapor density (air = 1), 3.14; sp.heat (water = 1), 0.4041 at 20°C.; flash point (closed cup), 4.44°C.; ignition temperature, 552°C.; explosive limits with air, 1.27–7.0% by vol.; parachor, 245.66 at 20°C.; dielectric constant, 2.24 at 20°C.; dipole moment ($\times 10^{18}$), 0.36.

Table I gives the boiling points of toluene at various pressures (9). Table II lists, for various temperatures, the values of viscosity, density, surface tension; for 20°C. only, the values of rate of change of density with temperature, molal volume, molecular refraction, specific refraction, specific dispersion, and refractivity intercept (9).

Some thermodynamic properties of toluene are: critical temp., 320.8°C.; crit. pressure, 40 atm.; crit. density, 0.29 g./ml.; crit. vol., 0.32 liter/mole; entropy of vaporization at b.p., 20.85 e.u.; heat of vaporization at b.p., 86.8 cal./g. Other properties of the liquid phase at 25°C. are: heat of formation, 2.867 kg.-cal./mole; entropy, 52.48 e.u.; free energy, 27.282 kg.-cal./mole; heat of combustion at constant pressure, 10,142.8 cal./g. gross and 9,686.1 cal./g. net; heat of fusion, 1.582 kg.-cal./mole; entropy of fusion, 8.879 e.u.; cryoscopic constant A, 0.02508 mole fraction per degree, and constant B, 0.0019 mole fraction per degree.

For calculating the purity of a nearly pure sample of toluene from its cryoscopic constants, the following equation may be used:

$$\log_{10} p = 2.00000 - (A/2.30259)(178.169 - T)[1 + B(178.169 - T)]$$

where p is mole percentage purity and T is freezing point of the sample in degrees Kelvin.

TABLE I. B.p. of Toluene at Various Pressures.

Vapor pressure, mm. Hg	10	50	100	200	400	600	760	800	1000	1500
Temperature, °C.	6.36	36.394	51.940	69.498	89.484	102.511	110.625	112.440	120.57	136.42

TABLE II. Physical Properties of Toluene at Various Temperatures.

Property	Temperature, °C.				
	−20	0	20	25	50
Viscosity:					
Centipoise	1.07	0.773	0.5866	0.5516	0.4189
Centistoke	1.18	0.873	0.6767	0.6397	0.4991
Density, g./ml.	0.9038	0.8854	0.8669	0.8623	0.8392
Change of density with temperature, g./ml./°C.	—	—	0.0092	—	—
Surface tension, dynes/cm.	—	30.92	28.53	27.92	25.04
Molecular volume, ml./mole	—	—	106.275	—	—
Molecular refraction	—	—	31.095	—	—
Specific refraction	—	—	0.33749	—	—
Specific dispersion, $10^4 (\eta_F - \eta_C)/D$	—	—	185.0	—	—
Refractivity intercept, $n_D - D/2$	—	—	1.06346	—	—

TABLE III. Thermodynamic Functions of Toluene for the Ideal Gas State.

Function	Temperature, °K.	
	298.16	1200
Heat content, $(H° - H°_0)/T$, cal./deg. mole	14.44	41.99
Free energy, $(F° - H°_0)/T$, cal./deg. mole	−61.98	−98.77
Entropy, $S°$, e.u.	76.42	140.76
Enthalpy, $H° - H°_0$, cal./mole	4,306	50,390
Heat capacity, $C°_p$, cal./deg. mole	24.80	66.90
Heat of formation, $\Delta H°_f$, kg.-cal./mole	11.950	5.27
Free energy of formation, $\Delta F°_f$, kg.-cal./mole	29.228	90.50
Equilibrium constant of formation, $\log_{10} K_f$	−21.4236	−16.4825

Table III gives values of thermodynamic functions of toluene for the ideal gas state at two temperatures (9).

Infrared data are useful in the analysis for toluene in the presence of xylenes and ethylbenzene. For that purpose measurements of absorption are made at 13.69 microns and at 14.07 microns, where toluene has distinctively strong and weak absorptions, respectively. However, in the presence of benzene it is preferable to use the ultraviolet spectrogram for analysis. The absorption is recorded in terms of the specific absorption coefficient according to Beers' law for optical density. Measurements are made at 252.5, 254.5, and 259 millimicrons for benzene and at 267 and 268.5 millimicrons for toluene.

Toluene is miscible in all proportions with alcohol, chloroform, ethyl ether, acetone, and carbon disulfide. At 16°C. its solubility in water is 0.047 g. per 100 ml. When it is distilled with steam at 760 mm. Hg the boiling point is 84.5°C. and the vapor contains 44.2 mole per cent water. The solubility of water in toluene is 0.15 mole per cent at 10°C. and 0.42 at 37.8°C. For toluene the aniline point is below −30°C.; since aniline has a freezing point of −6°C. it is customary to measure instead the mixed aniline point, which, by A.S.T.M. method D1012, is 10°C.

REACTIONS

The industrially useful chemical reactions of toluene may be grouped conveniently into three types, in which the reagent toluene is considered as being, respectively, benzyl hydride ($C_6H_5CH_2H$), phenylmethane ($C_6H_5CH_3$), and methylbenzene (CH_3-C_6H_5). The chief class of reaction for all three types is the substitution of hydrogen. For instance, chlorine can be substituted for one atom of hydrogen in benzyl hydride, for three atoms of hydrogen in phenylmethane, and for five atoms of hydrogen in the benzene ring of methylbenzene.

When substitution occurs in the ring, the industrially useful reactions are chiefly those yielding monosubstituted and trisubstituted products. When one hydrogen atom in the ring is substituted, three isomers are possible; ortho, meta, and para.

When two like substituents, other than methyl, occur on the ring, six isomers are possible. When three like substituents other than methyl are on the ring, six isomers are possible. If two unlike substituents are present, ten isomers are structurally possible. The multiply substituted isomers are named by assigning numbers, from 2 to 6, clockwise, to the carbon atoms around the ring from the number one carbon atom which holds the methyl group.

Chlorination. Substitution of hydrogen atoms in the methyl group of toluene is obtained by passing dry chlorine through boiling toluene, preferably in sunlight, there being formed progressively benzyl chloride ($C_6H_5CH_2Cl$), benzal chloride (C_6H_5-$CHCl_2$), and benzotrichloride ($C_6H_5CCl_3$). See Vol. **3**, p. 822.

Hydrogen atoms are substituted in the benzene ring of methylbenzene at room temperature by the action of chlorine in the absence of light and in the presence of a catalyst like iodine, phosphorus, sulfur, iron, ferric chloride, antimony pentachloride, or aluminum chloride.

Monochlorination of the ring yields preferentially *p*-chlorotoluene and secondarily *o*-chlorotoluene. The latter is a liquid; d_4^{20} 1.08; f.p. −35°C.; b.p. 159.3°C. It is used as a solvent, as a dye intermediate, and in other organic syntheses. By oxidation with potassium permanganate it yields *o*-chlorobenzoic acid, which is used as a preservative for glues and paints and as an intermediate in the manufacture of fungicides and dyes.

Sulfonation. When toluene is treated at 75°C. with sulfuric acid of 96–100% strength, the product is a mixture of 75% *p*-, 19% *o*-, and 6% *m*-toluenesulfonic acid. Their calcium salts are freely soluble in water; this solubility is used to free them from sulfuric acid because the calcium sulfate is relatively insoluble. See *Toluenesulfonic acids.*

Nitration. Three moles of toluene treated at 60°C. with a nitration mixture of three moles of nitric acid and three moles of sulfuric acid yield a mixture containing 60% *o*-nitrotoluene and 30% *p*-nitrotoluene. See Vol. **9**, p. 395.

Nitration at 70–90°C. of *o*-nitrotoluene yields 2,4-dinitrotoluene and 2,6-dinitro-

toluene; while *p*-nitrotoluene yields only 2,4-dinitrotoluene. Both products on further nitration yield the explosive TNT (see Vol. **6,** p. 42), 2,4,6-trinitrotoluene.

Manufacture

For the production of toluene from light oils derived from coal and gas, see Vol. **2,** p. 428.

TOLUENE FROM PETROLEUM

Crude oil as recovered from oil wells nearly always contains toluene; but only rarely does the concentration of toluene exceed 1% by volume. Among a group of fifteen typical American crude oils, Conroe had 2% by volume of toluene and a minimum of 2.00% methyl cyclohexane; Kettleman Hills oil had 0.70% toluene and a minimum of 1.68% methyl cyclohexane; North Sweden mixture had 0.80% toluene and 2.96% methyl cyclohexane; Tomball mixture had 1.1% toluene and 1.68% methyl cyclohexane. The remaining oils in the group had from 0 to 0.5% toluene.

In the normal handling of crude oil, the toluene becomes more highly concentrated in a distillate, which is called prime-cut or virgin naphtha and which typically is no more than 20% by volume of the original crude oil. It is possible to recover toluene from virgin naphtha by processes of fractional distillation, solvent extraction, and selective adsorption on silica gel; but on account of the initially low concentration of toluene, relatively large volumes of the naphtha have to be processed and therefore it is not usually economical to use virgin naphtha as a source of toluene directly. However, between 1935 and 1940, several million gallons of lacquer diluent, consisting of a concentrate of about 70% toluene prepared from virgin naphtha, such as that from Conroe crude, by such processes of fractional separation, were used industrially.

As early as 1918, not long after the first use of the cracking process for thermal decomposition of petroleum, it was known that the cracked naphthas had higher concentrations of toluene than virgin naphthas, and three plants were built for making nitration-grade toluene from cracked naphtha. The operation was uneconomical, partly because the yield was only 6% and partly because the cracked naphtha contained substantial proportions of olefinic hydrocarbons, which complicated the purification of toluene. Newer techniques of cracking at high temperature and utilizing the by-products, as in the Catarole process, have improved the economics, but other processes are more generally used.

Between 1928 and 1935, the difficulty caused by olefinic hydrocarbons was overcome by the development of a modification of the Bergius high-pressure hydrogenation process. The new method subjected aromatic naphthas to cracking temperatures at a total pressure of about 100 atm. with a low partial pressure of hydrogen in the presence of a catalyst. A typical raw material for the process was an aromatic extract from the refining of kerosine by the Edeleanu process (see Vol. **10,** p. 149) of liquid-phase extraction with sulfur dioxide. The extract contained substantial proportions of higher homologs of toluene, alkylated aromatic hydrocarbons, which, in effect, were partly dealkylated in that process to produce toluene. Commercial quantities of lacquer diluent, containing about 70% toluene, were produced by that method; but it was found less economical than the extraction of naturally occurring toluene in virgin naphtha of the sort which at that time became available from crude oils like Conroe and Kettleman Hills.

Hydroforming. In 1941, the modern process of hydroforming at moderate

pressure was fully developed and adapted to make nitration-grade toluene to fulfill a demand which exceeded the capacity of existing plants to supply from light oil of coal origin.

The basic principle of hydroforming is to dehydrogenate methyl cyclohexane to methylbenzene with heat in the presence of a catalyst. Crude oils usually contain considerably more methylcyclohexane than toluene. The boiling points of the two hydrocarbons are only about 9.5 °C. apart, so that both are conveniently concentrated in a single distillate from crude oil. Accordingly, the raw material or feed for hydroforming is typically a virgin naphtha with a range of boiling points between 93 °C. and 121 °C., which includes the boiling points of the two hydrocarbons to be concentrated.

The feed is heated to about 500 °C. at a pressure of 17 atm., first by heat exchange with the products leaving the reactor and then by passage through tubes heated in a furnace. The hot vapor of the feed is mixed with heated recycle gas, which contains from 40 to 80% by volume of hydrogen stripped from the reaction products in a gas separator.

The mixture of hot vapor and gas is introduced into one of two parallel reactors, or rows of reactors, partly filled with a fixed bed of molybdena-alumina catalyst. The products of reaction are withdrawn and cooled by heat exchange with the feed, as mentioned above, and with water in a second heat exchanger. The partly condensed products are introduced into a gas separator, whence part of the gas becomes recycle gas, as mentioned above, and the remainder of the gas is released as necessary for controlling the pressure of the system. The net production of hydrogen is about 200 liters per liter of feed. From the bottom of the gas separator, the liquid products go to a distillation column, called a stabilizer, in which propane and lighter hydrocarbon gases formed by thermal decomposition of the feed in the reactor are removed by fractionation from the stabilized liquid product, now containing all the toluene—both the original toluene of the feed and the toluene made by hydroforming.

During the reaction the catalyst becomes gradually contaminated by coke, which impairs the catalytic activity. At intervals of about 16 hours, the feed is diverted to the other parallel reactor system, and then the partly spent catalyst in the first reactor system is regenerated by burning off the coke with air, which is diluted with some of the gaseous product of that combustion.

Hydroforming is an endothermic process. In a tall reactor, with the feed entering at one end and the product leaving at the other, there is an undesirably large drop in temperature from inlet to outlet. Accordingly, it is better to use two short reactors in series, with a reheating furnace between them, instead of one tall reactor. Since the flow is diverted at intervals as mentioned above, a total of 4 short reactors is used in the system.

Although the chief reaction in the process is the dehydrogenation of methylcyclohexane, other reactions occur. For instance, *n*-heptane, which is often present in the feed, is partly cyclicized to toluene; but about one-fourth of the heptane is simultaneously cracked to "dry gas" including hydrogen and hydrocarbon gases more volatile than butane. The maintenance of a partial pressure of hydrogen during hydroforming accounts for the relatively low formation of coke. The products of the cracking reaction are largely olefinic; and at the temperature of reaction, in the absence of sufficient hydrogen, they tend to polymerize and to accumulate upon the catalyst as coke.

Other Re-Forming Methods. There are several commercial processes of catalytic re-forming based upon the principles outlined above but differing in technique. The choice of a process is determined by such variables as the nature of the feed, the extent of re-forming required, and the size of the plant to be built. Four principal types of catalyst are used. In fluid hydroforming, the catalyst type is molybdena-alumina, utilized in a fluidized bed instead of a fixed bed. Platinum-type catalysts are used in platforming, catforming, and Houdriforming. Cobalt molybdate is used in hyperforming, and chrome-alumina is used in a moving bed in Thermofor catalytic re-forming. See *Petroleum (refinery processes)*.

Concentration. The stabilized liquid product from hydroforming or other catalytic re-forming processes has an aromatic content of about 50%, which requires further concentration and purification when industrial-grade toluene or nitration-grade toluene is desired. Commercial methods of concentration include fractional distillation, extractive distillation, azeotropic distillation, solvent extraction, and selective adsorption. The typical adsorbent for selective adsorption is silica gel, which adsorbs aromatic hydrocarbons preferentially and from which they can be recovered by heating or by elution.

Commonly, some suitable combination of two or three of the first four methods is used in the petroleum industry. They may be classified in two types, vapor-liquid and liquid-liquid. In practice they are combined to obtain maximum separation selectivities for toluene. It has been shown that the separation selectivities for liquid-liquid extraction and vapor-liquid extraction are fundamentally related to the separation selectivity, commonly designated α, for distillation of two components under conditions where the vapors behave substantially like perfect gases. The relationship is: $\alpha\beta = g$, where β is the separation selectivity for liquid-liquid extraction and g for vapor-liquid extraction (6).

Let: Y_1 and Y_2 be the mole fractions of two components at equilibrium in the vapor; X_1 and X_2 be their mole fractions in the liquid at equilibrium; p be the total pressure in the system; P_1 and P_2 be the vapor pressures of the two components; and γ_1 and γ_2 be the "activity coefficients," a measure of deviations of the liquid from ideal behavior.

Then:

$$pY_1 = \gamma_1 X_1 P_1 \text{ and } pY_2 = \gamma_2 X_2 P_2$$

but since by definition:

$$\alpha = (Y_1/Y_2)(X_2/X_1)$$

then:

$$\alpha = (\gamma_1 P_1)/(\gamma_2 P_2)$$

When $\alpha = 1$, an azeotrope exists.

The ratio of the activity coefficients, γ_1/γ_2, for the nonaromatic hydrocarbon component and toluene, respectively, is called the "improvement factor." Obviously, if the ratio of the vapor pressures is the reciprocal of the improvement factor, an azeotrope occurs; and the two components cannot be separated by distillation unless a third component, capable of forming another azeotrope with one of the first two components, is introduced.

Azeotropic distillation processes have been used commercially to concentrate

toluene to high purity after the maximum practicable concentration by ordinary fractional distillation has been reached. Typically, methanol is used as the azeotrope former. A mixture of toluene concentrate with enough methanol to form an azeotrope with the nonaromatic portion of the concentrate is fed to a fractionating column having 20 plates and at a reflux ratio of 20 to 1, for example. The "bottoms" from the column has at least 96% toluene, which is refined to nitration grade by treatment with sulfuric acid and by redistillation in a separate still. The azeotropic distillate from the column mentioned above contains between 55 and 70% methanol, which is recovered by solution in water and by distillation for re-use. The percentage recovery of toluene of 99% purity with each of four efficient azeotrope formers is as follows:

Azeotrope former	Per cent recovery of toluene in feed
Aqueous methyl ethyl ketone	100
Nitromethane	95
Methanol	93
Dioxane	84

Extractive distillation may be used instead of azeotropic distillation to purify toluene. The solvent may be phenol, cresols, furfural, aniline, or alkyl phthalates. Phenol is commonly used. It is fed near the top of a distillation column and flows countercurrently to the vapors of the toluene-containing naphtha, which is fed near the bottom of the column. From the bottom, a phenol extract of toluene is withdrawn and fed to a stripper column, from the top of which toluene is distilled and from the bottom of which phenol is withdrawn for re-use in the first distillation column.

A very successful commercial method for separating nitration-grade toluene from hydroformed naphtha is the *liquid-liquid extraction* process, using liquefied sulfur dioxide and paraffinic "wash oil" in a twofold operation. The stabilized, fractionally distilled, hydroformed naphtha containing about 50% toluene is mixed with liquid sulfur dioxide at about −30 °C. in an extraction tower, from the bottom of which an extract is withdrawn. The extract is a solution, in sulfur dioxide, of a mixture of hydrocarbons of which toluene constitutes about 70%. The other hydrocarbons in the extract are nonaromatic. To remove them, the extract is treated countercurrently in a washing tower with a wash oil, which is typically a mixture of less volatile paraffinic hydrocarbons of the kerosine type and of which a part replaces the more volatile nonaromatic impurity in the extract. The excess of wash oil is taken from the top of the washing tower to be processed for re-use. The sulfur dioxide is stripped from the washed extract in a solvent recovery tower, from which a mixture of toluene and wash oil is drawn off. This mixture is treated with 98% sulfuric acid, at the rate of 10 or 20 pounds of acid per barrel of mixture, and then washed with caustic solution to neutralize any acid remaining from the previous treatment. The treated mixture is fractionally distilled in a re-run tower and nitration-grade toluene is recovered as the distillate.

In another commercial liquid-liquid extraction process, the solvent is aqueous diethylene glycol. The catalytically re-formed naphtha feed does not need to be closely fractionated before extraction with that solvent and the extract may be a mixture of benzene, toluene, and xylenes, containing less than 0.2% nonaromatic hydrocarbons; while the raffinate, the concentrate of nonaromatic hydrocarbons, contains no more

than 5% aromatics. The aromatic extract is refined by treating with activated clay under conditions favorable for polymerizing olefinic impurities. One ton of clay has been used for refining a total of 336,000 gallons of aromatic extract. The three aromatic hydrocarbons, benzene, toluene, and xylene, are recovered as distillates successively from three 40-tray fractionating columns in series, each column being operated at a pressure of 5 p.s.i.g.

Separation Selectivity. The selection of a solvent for any of the four methods of concentrating toluene has hitherto been based wholly on empirical and economical considerations. However, a study of separation selectivities indicates that the choice of a solvent can be made on the basis of the magnitude of the deviation of its solutions from compliance with Raoult's law (6). If a solution of toluene in a solvent follows Raoult's law fairly closely, while a corresponding solution of the saturated hydrocarbons to be separated from toluene departs widely from the law, the solvent fulfills the basic requirement for effecting the desired separation.

To get quantitative measures of the separation selectivities, the following procedure is used. The partial pressures of various mixtures of the solvent with the saturated hydrocarbons are measured at the temperature at which separation is to be made. The ratios of the observed partial pressures of the hydrocarbons to their partial pressures, as calculated by Raoult's law, are plotted against the concentrations; and the graph is extrapolated to the value for infinite dilution. The value of this ratio at infinite dilution is called J_s. The same sort of graph is made for toluene and the ratio J_t is obtained.

Then the separation selectivity, β, for liquid-liquid extraction is J_s/J_t, a value potentially attainable whenever two liquid phases exist in the system of three liquids. The separation selectivity, g, for vapor-liquid extraction, is J_sP_s/J_tP_t, where P_s and P_t are the vapor pressures of the hydrocarbons being separated and where α, the separation selectivity for distillation, is P_s/P_t, on the assumptions that the mixture of toluene and saturated hydrocarbons, in the absence of the solvent, is a perfect solution and that Raoult's and Henry's laws are applicable.

Specifications

The American Society for Testing Materials has issued standard specifications for two grades of toluene, nitration grade D841–50 and industrial grade D842–50. They conform with the requirements shown in Table IV, which also lists the A.S.T.M.

TABLE IV. Summary of A.S.T.M. Standard Specifications for Toluene.

Requirement	A.S.T.M. test to be used	Nitration grade, D841–50	Industrial grade, D842–50
Sp.gr. 15.56/15.56°C.	D891	0.8690–0.8730	0.864–0.874
Acid wash color, max. no.	D848	2	4
Acidity, max. allowable	D847	None	None
H_2S and SO_2, max. allowable	D853	None	None
Paraffins, vol. %, max. allowable	D851	1.5	Not specified
Color, max. allowable	D853	Not darker than solution of 0.0030 g. $K_2Cr_2O_7$ in 1 liter H_2O	
Distillation range, max. allowable	D850	1°C. Including the temperature of 110.6°C.	2°C.
Copper corrosion, max. allowable	D849	No iridescence, nor gray, nor black deposit or discoloration	

designations of the methods of test to be used. See Vol. 2, p. 438. They serve to define the relative purity of the two grades of toluene, the one for nitration and other reactions, the other for industrial uses as a solvent.

Shipping

Commercial grades of toluene are shipped in the same type of containers as benzene (see Vol. 2, p. 435). All shipping containers must comply with specifications of the U.S. Interstate Commerce Commission. To each container an approved caution tag is to be attached. Tank cars and box cars transporting toluene must bear the I.C.C. "dangerous" placard; and drums and boxes must bear the I.C.C. red label for flammable liquids.

Health and Safety Factors

The acceptable limit of concentration of toluene vapor in air is 200 p.p.m., or 0.75 mg. per liter, for workers exposed to it no longer than 8 hours daily. A lower concentration is desirable because at the limit there are slight impairment of coordination and slowing of reaction time among the workers. The limit of sensory acceptability, from the viewpoint of eye irritation, is 300 p.p.m.; but concentrations even higher than 400 p.p.m. have been tolerated by workmen without complaint. Therefore, sensory response is not reliable as a warning of the presence of dangerous concentrations. At any given temperature of the liquids, toluene, having a lower vapor pressure then benzene, gives lower concentration of vapor in air and therefore produces less poisoning, and toluene does not have the neurotoxic effect of benzene. However, their narcotic effects are comparable at equal concentrations. The chronic and cumulative effects produced by toluene are less severe and dangerous than those resulting from benzene. On the human skin, toluene exerts an irritant action similar to but stronger than that of benzene.

Economic Aspects

In the U.S., the plant capacity planned to be used in 1955 for producing commercial grades of toluene has been estimated at 186 million gallons per year, compared with actual production of about 100 million gallons in 1951. Since 1942, the major source of toluene has been from petroleum. For instance, in 1944, the American petroleum industry produced 105 million gallons of toluene, compared with 30 million gallons from coal sources. In 1949, the production of toluene from petroleum was 48 million gallons; and from coal sources 34 million gallons. Before 1941, the sole source of pure toluene was coal. Production in 1940 was 30 million gallons; in 1922, 2 million gallons; and in 1918, 9 million gallons. Apart from the important demand for toluene to make TNT in wartime, the demand for toluene has increased steadily since about 1925 chiefly as a result of its uses as blending agent in aviation gasoline and as a solvent or diluent in coating compositions based on synthetic lacquers, resins, rubbers, and polymers.

The United States Business and Defense Services Administration published the data in Table V showing the estimated consumption of toluene by industry for the years 1950 to 1952.

For 1950, the U.S. Tariff Commission estimated that the total sales of crude toluene from petroleum for chemical conversion were 235,458,000 lb. with an average

TABLE V. Estimated Consumption of Toluene by Use.

End use	Toluene consumed, thousands of gallons		
	1950	1951	1952
Total consumption	76,032	94,692	95,469
Aviation gasoline	27,996	35,827	40,169
Explosives	722	6,700	24,496
Chemical synthesis	13,975	18,629	17,161
Protective coatings and solvents	28,246	27,817	8,957
Medicines and pharmaceuticals	1,232	1,860	1,684
Rubber derivatives	1,414	1,390	1,404
Dyes	852	813	630
Petroleum refining	547	623	635
Miscellaneous	1,048	1,033	333

value of 3.2 cents per pound. In 1953, the average value was 4.1 cents per pound for all grades and 4.5 cents per pound for nitration grade.

Uses

The use to which toluene is to be put determines the degree of purification to which it needs to be refined. Typical ranges of purity for important uses are as follows:

Range of purity, %	Use for toluene
100–99	*Nitration and other reactions*
98–95	Solution and dilution of resins for coatings
94–75	Aviation gasoline and solvents
74 and less	Motor gasoline blending

Chemical. See p. 264.

Gasoline. The chief advantage of using toluene for blending in gasolines lies in its high antiknock quality. Toluene is less susceptible to knock than most of the hydrocarbons normally present in gasoline. For a discussion of engine knock and the use of antiknock agents, see Vol. **6**, p. 944. The antiknock quality of toluene is higher than 100 octane number. When tested by A.S.T.M. method D908, toluene equals isooctane containing 5.8 ml. of tetraethyl lead per gallon. When tested by A.S.T.M. method D357, toluene has the following ratings:

Ml. tetraethyl lead/gal. toluene.....	0	1	3
Motor method rating, ml. TEL/gal. isooctane	0.3	1.0	1.7

In order to obtain an estimate of the contribution that toluene makes to the octane number of a gasoline, one may use its *blending octane number*, which is simply the arithmetical contribution of a known percentage of toluene in a blend to the octane number of the blend, when the octane number of the material with which the toluene is blended is also known. For that purpose, A.P.I. project 45 has reported data on blends of 20% toluene and 80% of a mixture of 6 parts of isooctane and 4 parts of *n*-heptane, the latter mixture having 60 octane number by definition. The data are the following:

	Octane number of 20% blend	Blending octane number
Research method, D908	72.7	124
Motor method, D357	70.3	112

The blending octane number for this mixture would be obtained as follows:

$$0.2\,x + 0.8\,(60) = 72.7$$

$$x = 123.5$$

For use in aviation gasoline, toluene is particularly desirable. Its antiknock quality is not only high when it is used in lean mixture with air as is required for economical operation under cruising conditions of aircraft using gasoline engines, but is also higher than for many other hydrocarbons when used in rich mixture with air as is required for maximum power under take-off conditions of aircraft. For aviation gasoline, the antiknock quality is measured by A.S.T.M. method D614 for lean mixture and by method D909 for rich mixture. A typical aviation gasoline is grade 100–130 as defined in A.S.T.M. specification D910. The grade numbers mean that this gasoline in a typical aviation engine can deliver 100% of the knock-limited power which pure isooctane can deliver in the same engine in lean fuel-air mixture, and in a similar manner, 130% in rich mixture. These grade numbers are called performance numbers. For comparison, the performance numbers of isooctane and toluene in 20% concentration in grade 100–130, when the complete blend contains 4 ml. of tetraethyl lead per gallon, have been calculated arithmetically to be as follows:

Hydrocarbon (tested at 20% concentration with 4 ml. TEL/gal.)	Performance numbers, calculated for: Method D614	Method D909
Isooctane	153	153
Toluene	102	237

Solvents. The chief industrial application of toluene as a solvent is to dissolve or dilute compositions for protective coatings. The class of protective coatings in that definition includes not merely paints, varnishes, lacquers and enamels but also coated fabrics, floor coverings, wall coverings, and artificial leather. See *Solvents, industrial.*

The first important industrial use of toluene in the formulation of a protective coating was as the diluent for nitrocellulose lacquers, which were fully developed in the early 1920's for coating automobiles and other mass-produced items of consumers' durable goods.

In the 1930's, the plastics industry made great strides in developing synthetic resins for use in protective coatings. Many hard resins, both natural and synthetic, require the use of toluene as a solvent. Examples of resins, in the manufacture or application of which toluene is used as a solvent, are the alkyd resins, made from phthalic anhydride and glycerol, the coumarone-indene resins, the melamine resins, the pure and the modified phenolics made from phenol and formaldehyde, and the urea-formaldehyde resins. Toluene is used for thinning vinyl organosols. It is also used for making rubber cements in the application of the relatively insoluble synthetic rubbers made with acrylonitrile, and for dissolving the inks used in printing synthetic-coated floor coverings and textiles.

Toluene itself, as a standardized industrial solvent, is used in tests of other solvents, as for example, in A.S.T.M. D268 for measuring toluene dilution ratio (see Vol. **12,** p. 660); in D1134, a test for nitrocellulose diluting power of hydrocarbon solvents; and D1133, a test for the Kauri-Butanol value of hydrocarbon solvents.

Bibliography

(1) A.P.I. Toxicological Review, *Toluene*, March 1948; American Petroleum Institute Department of Safety, 50 W. 50th St., New York 20, N.Y.
(2) A.S.T.M. Standards, 1952, Part 5.
(3) Associated Factory Mutual Fire Insurance Co., *Properties of Flammable Liquids, Gases, and Solids* (Loss Prevention Bull. No. 36.10), Boston, 1950.
(4) Dickerman, W. C., "The Present Status of the Art of Cracking Petroleum Fractions," *J. Inst. Petroleum, London*, **39**, 783 (1953).
(5) Grignard, V., *Précis de Chimie Organique*, Masson & Cie., 1942, Paris, France.
(6) Hibshman, H. J., "Separation of Hydrocarbons by Solvent Extraction," *Ind. Eng. Chem.*, **41**, 1366–74 (1949).
(7) Love, R. M., and Pfennig, R. F., "Aromatics from Petroleum," in *Progress in Petroleum Technology*, pp. 299–309, Sept. 1951; American Chemical Society, 1155 Sixteenth St., N.W., Washington, D.C.
(8) Maisel, D. S., "Aromatics from Petroleum," *Petroleum Processing*, 8, 1185–92 (1953).
(9) "Selected Values of Properties of Hydrocarbons," American Petroleum Institute Research Project 44, Natl. Bur. Standards (U.S.) Circ. 461 (1947).

MAURY LAPEYROUSE

TOLUENEDIAMINES, $CH_3C_6H_3(NH_2)_2$. See *Phenylenediamines*, Vol. **10**, p. 379.

TOLUENE SUBSTITUTE. See *Petroleum (products)*, Vol. **10**, p. 167.

TOLUENESULFONAMIDES, $CH_3C_6H_4SO_2NH_2$. See *Sulfonamides*, Vol. **13**, pp. 313, 314; *Toluenesulfonic acids*.

TOLUENESULFONIC ACIDS AND TOLUENESULFONYL CHLORIDES

Mono-, di-, and trisulfonic acids of toluene have been prepared; of these, the most important from a commercial standpoint are the toluenemonosulfonic acids, $CH_3C_6H_4SO_3H$, and the corresponding acid chlorides, toluenesulfonyl chlorides, $CH_3C_6H_4SO_2Cl$. Commercial toluenesulfonic acid, produced by direct sulfonation of toluene with sulfuric acid, is a mixture of the ortho and para isomers with a small amount of the meta isomer. A similar mixture of the sulfonyl chlorides is obtained by direct sulfonation with chlorosulfonic acid.

Toluenemonosulfonic acids were first prepared by Jaworsky in 1865 by sulfonating toluene with sulfuric acid. The presence of two isomers in the sulfonic acid mixture was established in 1869 by Engelhardt and Latschinoff, and in 1870 Wolkow determined the structures of these two isomers by fusing them with alkali. Klason, in 1886, and Holleman and Caland (7), in 1911, showed by indirect means that the sulfonic acid mixture also contained some of the meta isomer. Beckurts and Otto first chlorosulfonated toluene in 1878, and in 1879 Klason and Wallin showed that the sulfonation mixture contained all three isomeric toluenesulfonyl chlorides.

The toluenesulfonic acids are used as intermediates in the preparation of many commercially important derivatives.

Physical and Chemical Properties

***o*-Toluenesulfonic acid,** $CH_3C_6H_4SO_3H$, formula weight 172.19, m.p. 67.5°C., forms a deliquescent dihydrate. This isomer is stable on heating to 100°C., but slowly changes to the para isomer at 140–150°C. ***p*-Toluenesulfonic acid,** $CH_3C_6H_4SO_3H$,

formula weight 172.19, m.p. 38°C., forms a white crystalline monohydrate melting at 106°C. Both the *o*- and *p*-toluenesulfonic acids are very soluble in water and alcohol and slightly soluble in benzene and toluene. The para isomer is slightly soluble in ether, whereas the ortho isomer is insoluble.

***o*-Toluenesulfonyl chloride,** $CH_3C_6H_4SO_2Cl$, formula weight 190.64, m.p. 11.2°C., b_{10} 126°C., d_4^{20} 1.3383, is an oil which is very soluble in most organic solvents but insoluble in water. ***p*-Toluenesulfonyl chloride,** m.p. 67.4°C., b_{10} 134.5°C., forms colorless triclinic or rhombic crystals. This isomer is also soluble in organic solvents and insoluble in water. The ortho and para isomers form a eutectic mixture, m.p. 1.7°C., containing 17.5% para isomer.

The chemical properties of the strongly acidic toluenesulfonic acids are in general those of aromatic sulfonic acids (see *Sulfonic acids*). Many salts have been described; most metallic salts are quite water-soluble. When heated in the presence of water vapor, toluenesulfonic acids decompose to give toluene and sulfuric acid. When fused with excess potassium hydroxide, *o*- and *p*-toluenesulfonic acids yield the corresponding cresols:

$$CH_3C_6H_4SO_3K + 2\,KOH \longrightarrow CH_3C_6H_4OK + K_2SO_3 + H_2O$$

$$2\,CH_3C_6H_4OK + H_2SO_4 \longrightarrow 2\,CH_3C_6H_4OH + K_2SO_4$$

Oxidation of potassium toluenesulfonates with neutral potassium permanganate yields the sulfobenzoic acids, $HOOCC_6H_4SO_3H$.

Toluenesulfonyl chlorides are formed from the sulfonic acids and phosphorus pentachloride:

$$CH_3C_6H_4SO_3H + PCl_5 \longrightarrow CH_3C_6H_4SO_2Cl + POCl_3 + HCl$$

The sulfonyl chlorides can be more conveniently produced by chlorosulfonation of toluene (see under "Manufacture").

Toluenesulfonyl chlorides hydrolyze in the presence of water to give toluenesulfonic and hydrochloric acids. Esters can be formed from toluenesulfonyl chlorides and alcohols or phenols in the presence of alkali:

$$CH_3C_6H_4SO_2Cl + CH_3OH + NaOH \longrightarrow CH_3C_6H_4SO_3CH_3 + NaCl + H_2O$$

Reaction of toluenesulfonyl chlorides with ammonia or amines yields sulfonamides (*q.v.*):

$$CH_3C_6H_4SO_2Cl + 2\,NH_3 \longrightarrow CH_3C_6H_4SO_2NH_2 + NH_4Cl$$

Toluenesulfonyl chlorides can be reduced with zinc dust to sulfinic acids and thiocresols.

Further sulfonation of toluenemonosulfonic acids with oleum at high temperature yields mainly toluene-2,4-disulfonic acid; sulfonation under similar conditions with excess chlorosulfonic acid gives mainly toluene-2,4-disulfonyl chloride. Toluene-2,4,6-trisulfonic acid is produced by heating potassium toluene-2,4-disulfonate at 240°C. with three molecular equivalents of chlorosulfonic acid.

Manufacture

The commercial sulfonation of toluene is accomplished according to the following equation:

$$CH_3C_6H_5 + H_2SO_4 \rightleftharpoons CH_3C_6H_4SO_3H + H_2O$$

Most commercial processes utilize some means of removing water of reaction so as to force the reaction to completion. Toluene sulfonates more readily than benzene and with concentrated sulfuric acid, even at 0°C., the reaction proceeds at an appreciable rate. The ortho-para ratio of the product is dependent upon the temperature of sulfonation. At 0°C. the mixed sulfonic acids contain 53.5% para isomer, while at 100°C., the para isomer content increases to about 84% without appreciable change in the meta isomer content, which is generally quite low (3,7). The ratio of isomers is not affected appreciably by variations in acid concentration (3) or by addition of catalysts such as potassium, mercurous or silver sulfate, or boron trifluoride. *p*-Tolyl sulfone is often formed in small quantities as a by-product.

$$CH_3C_6H_4SO_3H + CH_3C_6H_5 \longrightarrow (CH_3C_6H_4)_2SO_2 + H_2O$$

The commercial chlorosulfonation of toluene is accomplished according to the following equations:

$$CH_3C_6H_5 + ClSO_3H \longrightarrow CH_3C_6H_4SO_3H + HCl \quad (1)$$

$$CH_3C_6H_4SO_3H + ClSO_3H \rightleftharpoons CH_3C_6H_4SO_2Cl + H_2SO_4 \quad (2)$$

Hydrogen chloride formed in reaction (1) escapes from the reaction mass as a gas (6,8). Various methods are employed in the commercial processes to drive reaction (2) to completion. The ortho–para ratio of the product is dependent here also on the reaction temperature. The lower temperatures normally used in chlorosulfonation favor formation of higher proportions of *o*-toluenesulfonyl chloride and also minimize formation of by-product *p*-tolyl sulfone.

Use of batch processing predominates in the commercial production of toluenesulfonic acids and toluenesulfonyl chlorides. See also *Sulfonation and sulfation.*

Toluenesulfonic Acids. The most commonly used processes for the sulfonation of toluene remove water of reaction by azeotropic distillation. These processes eliminate the use of excess sulfuric acid by maintaining a high acid concentration throughout the sulfonation. With careful control toluenesulfonic acids low in free sulfuric acid, sulfones, and disulfonic acids can be produced.

In a typical process, the sulfonator is charged with 50–60% sulfuric acid, which is heated to 120–180°C. An excess of toluene vapor, from a vaporizer, is passed through the acid. Unreacted toluene vapor mixed with water vapor leaves the reactor and is condensed. The resulting toluene and water layers are allowed to settle. The toluene layer is separated and, after drying, is recycled to the vaporizer for subsequent sulfonation. The acid concentration in the sulfonator gradually increases until the critical concentration required for sulfonation is reached. Sulfonation then begins and continues with the acid concentration remaining slightly above the critical limit. Water of reaction is removed continuously with excess toluene vapor. The reaction is stopped before all of the sulfuric acid has been converted to toluenesulfonic acids (5,15). The progress of the sulfonation is followed by determining the acidic titer of the reaction mixture at suitable intervals (13).

In another process, 90–95% sulfuric acid is gradually added to refluxing toluene. The temperature of the reaction mixture, which is vigorously agitated, is kept below 115°C. by using a 50–100% excess of toluene. The vapor mixture leaving the reactor is condensed and allowed to settle. The water layer is discarded and the toluene layer is returned to the reactor. Refluxing is continued until water present in the original sulfuric acid charge and 70–75% of the theoretical water of reaction have been removed. The refluxing operation requires 5–15 hours. The product contains 75–85%

p-toluenesulfonic acid, 10–20% of ortho isomer, 2–5% of meta isomer, less than 1% unreacted sulfuric acid, and only traces of *p*-tolyl sulfone (20).

In a third process, toluene is treated with sulfuric acid at atmospheric pressure until the reaction stops because of reduced acid concentration. The batch is then heated under vacuum to 150–180°C. Toluene vapors are passed through the reaction mass to remove water and increase the acid strength. By repeating alternately the sulfonation and dehydration operations it is possible to convert most of the sulfuric acid to toluenesulfonic acids (19). A modification of this process involves introducing liquid toluene into 80–98% sulfuric acid held above 120°C. under vacuum. The toluene is vaporized on contact with the acid but the reaction is rapid enough so that most of the toluene is sulfonated before it passes through the acid. Under the conditions used, water of reaction is removed and acid strength is maintained. Any unreacted toluene is condensed and recycled (16).

In a continuous process, toluene is sulfonated at 150°C. in a cast-iron reaction tower which contains baffle plates or some inert packing. Hot 98% sulfuric acid is allowed to flow downward through the tower while toluene vapor introduced near the bottom passes upward through the tower. Reaction occurs as the two materials contact one another. Unreacted toluene plus water of reaction leave the top of the tower as vapors and are condensed. Toluenesulfonic acids formed are washed downward by descending sulfuric acid and are discharged with any unreacted sulfuric acid through a liquid seal at the bottom of the tower (17,18).

In another continuous process, three separate streams of materials, liquid toluene, 98% sulfuric acid, and a recycled portion of sulfonation product, are introduced near the bottom of a tall reactor which is kept nearly filled with liquid reaction mixture. The three streams in admixture pass concurrently up through the reaction zone to the opposite end of the reactor. A stream of toluene vapor, introduced continuously at the bottom of the reactor, is removed along with water vapor at the top of the reactor. The liquid sulfonation product is removed near the top of the reactor and a portion is recycled (21).

The finished sulfonation mass usually contains dissolved toluene, which is removed by applying vacuum or by purging with an inert gas. The toluene-free sulfonation mass is sold in many cases without further treatment.

To separate the isomers, water or cold concentrated hydrochloric acid is added to the toluene-free sulfonation mass. *p*-Toluenesulfonic acid monohydrate crystallizes from the mixture. Higher yields are obtained with hydrochloric acid, in which the para isomer is practically insoluble. To obtain pure ortho isomer, the mother liquor from the para isomer crystallization is cooled to −5°C. The crude, crystalline ortho isomer is separated from the remaining para isomer and sulfuric acid as the barium salt, which is soluble in hot water in contrast to barium sulfate and less soluble in cold water than the salt of the para isomer. Thus barium (or calcium) salts may also be used to separate sulfuric acid from the toluenesulfonic acids.

Toluenesulfonyl Chlorides. In producing toluenesulfonyl chlorides, toluene is slowly fed into 95–100% chlorosulfonic acid contained in a cast-iron, jacketed sulfonating vessel provided with a suitable agitator. About 3½ parts of chlorosulfonic acid is used for 1 part of toluene. The excess acid used is sufficient to insure fairly complete conversion to the sulfonyl chlorides. The rate of toluene addition is controlled so as to maintain a temperature of 0–5°C. After all the toluene has been added, the reaction mass is stirred for an additional period at 5°C.

Larger excesses of chlorosulfonic acid, as much as 6 parts to 1 part of toluene, have been recommended (4). Addition of sodium chloride to the reaction mixture, alone or in combination with an organic solvent such as tetrachloroethane, reduces the excess chlorosulfonic acid requirements by removing the sulfuric acid formed as sodium hydrogen sulfate.

The finished sulfonation mass is quenched on ice and the crude toluenesulfonyl chlorides are separated from the acidic aqueous phase. After washing with water, the mixed sulfonyl chlorides are cooled to crystallize the relatively pure *p*-toluenesulfonyl chloride, which is removed by filtration. The liquid filtrate still contains some para isomer; a pure ortho isomer fraction may be obtained from this filtrate by distillation. Repeating alternately the crystallization and distillation operations affords a means of separating the isomers. In many instances mixtures of the sulfonyl chlorides are used without separation to produce commercially valuable derivatives; in other instances separation of isomers is performed after formation of derivatives.

Grades and Specifications

Technical toluenesulfonic acid is sold as a light greenish to black viscous liquid or semicrystalline mass, having the following specifications: toluenesulfonic acids, 94.0% min.; sulfuric acid, 1.0% max.; water, 2.0% max.; toluene, 0.2% max. This technical acid is a mixture of approximately 80% para isomer and 20% ortho isomer. It is packed in steel drums.

p-Toluenesulfonic acid monohydrate, which is a grayish-white to white crystalline material, is sold in small quantities.

The approximate sales price for toluenesulfonic acids in 1955 was 16–17.5¢ per pound.

Technical *p*-toluenesulfonyl chloride is sold in small quantities as a grayish-white or yellowish crystalline material having the following specifications: assay, 95% min.; crystallizing point, 65.5°C. min. The containers used are gumwood or paraffin-lined oak barrels holding 350–450 lb. of material.

Analysis

Commercial toluenesulfonic acids usually contain some sulfuric acid; in assaying such material on the basis of acidity, a correction for sulfuric acid content is necessary. In one method, the total acidity of a sample is determined by titrating with sodium hydroxide, using methyl orange indicator. A second sample of the material is dissolved in water and is heated to boiling after adding a small amount of hydrochloric acid. Barium sulfate is precipitated from this hot solution with 5% barium chloride solution. The percentage of free sulfuric acid is calculated from the weight of barium sulfate.

Technical *p*-toluenesulfonyl chloride is generally assayed as follows: A sample is hydrolyzed by treating with aqueous-alcoholic sodium hydroxide. After acidifying with nitric acid, the total chloride is determined by potentiometric titration with silver nitrate solution. This figure must be corrected for any free chlorides present in the original sample; the free chlorides are determined by suspending a second portion of the material in cold water with a small amount of toluene and titrating potentiometrically with silver nitrate solution.

Uses

Derivatives of the toluenesulfonic acids, prepared in many cases via the acid chlorides, are considerably more important than the free acids. Thus, the toluenesulfonamides and *N*-alkyltoluenesulfonamides, saccharin, chloramine T, alkyl toluenesulfonates, various resins, etc., all stem from the parent sulfonic acids. Relatively small quantities of the toluenesulfonic acids as such are used as mild acid catalysts for esterifications and condensations, in refining toluene, and in the manufacture of synthetic cresols. A few nitro- and aminotoluene sulfonic acids find use as dye intermediates.

Derivatives

Sodium 3-chloro-*p*-toluenesulfonate, $CH_3C_6H_3(Cl)SO_3Na$, formula weight 228.64, is prepared by chlorinating a water solution of sodium *p*-toluenesulfonate at about 20–25°C. The product is used in relatively small quantities as a dye intermediate.

Methyl *p*-toluenesulfonate, $CH_3C_6H_4SO_3CH_3$, formula weight 186.22, m.p. 29°C., b_9 146–147°C., is readily soluble in alcohol, benzene, or ether but is insoluble in water. It is prepared by treating *p*-toluenesulfonyl chloride with methanol in the presence of alkali. Methyl *p*-toluenesulfonate is used as a selective methylating agent. Severe skin irritations can result from contact with this ester.

Ethyl *p*-toluenesulfonate, $CH_3C_6H_4SO_3C_2H_5$, formula weight 200.25, is a crystalline material, m.p. 35°C., b_9 165–166°C. It has solubility characteristics similar to the methyl ester and is prepared from ethyl alcohol and *p*-toluenesulfonyl chloride in the presence of alkali. It is used as a selective alkylating agent.

Phenyl *p*-toluenesulfonate, $CH_3C_6H_4SO_3C_6H_5$, formula weight 248.29, m.p. 96°C., is prepared by reaction of sodium phenolate with *p*-toluenesulfonyl chloride. The product has similar solubility characteristics to the methyl ester. It is used as a plasticizer.

The *o*- and ***p*-toluenesulfonamides,** $CH_3C_6H_4SO_2NH_2$, formula weight 171.22, are white crystalline solids (see also *Sulfonamides*). The para isomer melts at 137.0°C. and is soluble in alcohol, slightly soluble in water and in ether, and insoluble in benzene. The ortho isomer melts at 156°C. and is generally less soluble in all solvents than the para isomer. Solubility of the sulfonamides in water is greatly increased in the presence of alkali. The toluenesulfonamides are formed by treating *o*- and *p*-toluenesulfonyl chlorides with ammonia. Considerable quantities of refined ortho and para amides are used as plasticizers (*q.v.*) for various resins; they have unusual properties which are of particular value to makers of molding compositions (9). Commercially useful resins result from the reaction of toluenesulfonamides with aldehydes (see *Amino resins and plastics*). *p*-Toluenesulfonamide yields chloramine T (the sodium derivative of *N*-chloro-*p*-toluenesulfonamide) on chlorination in alkaline solution (see *Chloramines*). Oxidation of *p*-toluenesulfonamide yields *p*-sulfamoylbenzoic acid, $HOOCC_6H_4SO_2NH_2$, an intermediate for halazone (*p*-(*N*,*N*-dichlorosulfamoyl)benzoic acid). Oxidation of *o*-toluenesulfonamide yields saccharin (*o*-sulfobenzoic imide) (10) (see *Sweetening agents*).

***N*-Ethyl-*p*-toluenesulfonamide,** $CH_3C_6H_4SO_2NHC_2H_5$, formula weight 199.27, m.p. 59°C., is prepared by treating *p*-toluenesulfonamide with ethyl sulfate in the presence of alkali or by treating *p*-toluenesulfonyl chloride with ethylamine. It is soluble in alcohols, esters, ketones, and aromatic hydrocarbons, and is insoluble in

water. *N*-Ethyl-*p*-toluenesulfonamide and mixtures with the ortho isomer are also used as plasticizers.

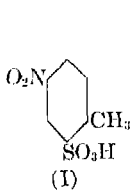
***N*-Cyclohexyl-*p*-toluenesulfonamide,** $CH_3C_6H_4SO_2NHC_6H_{11}$, formula weight 253.34, is a white crystalline solid, m.p. 86°C. It is soluble in alcohols, esters, ketones, and aromatic hydrocarbons, and is insoluble in water. This product is prepared from *p*-toluenesulfonyl chloride and cyclohexylamine and is used as a plasticizer.

α-Aminotoluenesulfonamide (Sulfamylon), see Vol. **13,** pp. 273, 280.

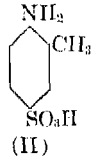
NITRO AND AMINO DYE INTERMEDIATES

5-Nitro-*o*-toluenesulfonic acid (I), $C_7H_7NO_5S$, formula weight 217.21, precipitates as colorless hydrated crystals from aqueous solutions, but they can be dried to the anhydrous form. The water-free crystals melt below 130°C., the hydrated form at about 130–33.5°C. The compound is readily soluble in water, alcohol, ether, and chloroform. It is produced by sulfonation of *p*-nitrotoluene (12). Over 2,000,000 lb. was produced in 1953. The compound is used in large quantities in the production of stilbene dyes (*q.v.*), for example, Sun Yellow (*C.I.* 620), Mikado Orange (*C.I.* 621), Diphenyl Orange RR (*C.I.* 626), Diphenyl Chrysoine G (*C.I.* 631), and Chicago Orange G (*C.I.* 633).

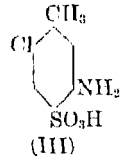
4-Amino-*m*-toluenesulfonic acid (II), $C_7H_9NO_3S$, formula weight 187.21, precipitates from aqueous solution as colorless needles which contain one equivalent of water of crystallization. The anhydrous form is produced by drying for several hours at 120°C. The compound does not have a definite melting point, and decomposes on heating in aqueous solution at 180–200°C. It is fairly soluble in water. It is generally produced by the reduction of the corresponding nitro compound. About 337,000 lb. was produced in 1953. It can also be prepared by the sulfonation of *o*-toluidine (1), or by rearrangement of the amine sulfate or acid sulfate. It is employed as an intermediate in the manufacture of Lithol Rubine B (*C.I.* 163), an azo dye which is the basic color for the manufacture of red pigments and is known also in its purified form as D&C Red No. 7.



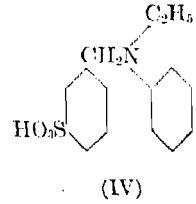
(I)



(II)



(III)



(IV)

2-Amino-5-chloro-*p*-toluenesulfonic acid (III), $C_7H_8ClNO_3S$, formula weight 221.5, is a white powder, difficultly soluble in water. It is produced from toluene by sulfonation, chlorination, nitration, and reduction (11). In 1953, 906,000 lb. was produced. It is employed as an intermediate in the production of the azo dye Lake Red C (*C.I.* 165), which is employed in the manufacture of red lakes and in D&C Reds Nos. 8 and 9, and in the manufacture of the azo dye Lithol Red 2G (*C.I.* 166), also used in lake manufacture.

α-(*N*-Ethylanilino)-*m*-toluenesulfonic acid (IV), $C_{15}H_{17}NO_3S$, formula weight 291.36, is precipitated from aqueous solution as colorless prisms containing one mole of water of crystallization. It becomes dehydrated at about 110°C., sinters at 160–170°C., and melts around 190°C. It is produced by sulfonation of ethylbenzylaniline, $C_6H_5N(C_2H_5)CH_2C_6H_5$; the product was formerly believed to be the para monosulfonic acid but is now considered to be chiefly the meta isomer (2a). In 1953,

299,000 lb. was produced. It is employed primarily in the production of triphenylmethane dyes (*q.v.*), for example, Guinea Green B (FD&C Green No. 1) (*C.I.* 666), Brilliant Milling Green B (D&C Green No. 7) (*C.I.* 667), Erioglaucine (FD&C Blue No. 1, D&C Blue No. 4) (*C.I.* 671), Acid Violet 6B (FD&C Violet No. 1, D&C Violet No. 1) (*C.I.* 697), and Formyl Violet S4B (*C.I.* 698). It has also been used in azo and thiazine dyes in the past.

Bibliography

(1) Allen, C. F. H., and Van Allan, J. A., *Organic Syntheses*, Wiley, N.Y., 1947, Vol. XXVII, p. 88.
(2) Beilstein, 4th ed., Vol. XI, pp. 83, 97; 1st Suppl., Vol. XI, pp. 22, 24; 2nd suppl., Vol. XI, pp. 39, 43.
(2a) Blangey, L., Fierz-David, H. E., and Stamm, G., *Helv. Chim. Acta*, **25**, 1162 (1942).
(3) Englund, S. W., Aries, R. S., and Othmer, D. F., *Ind. Eng. Chem.*, **45**, 189–93 (1953).
(4) Groggins, P. H., *Unit Processes in Organic Synthesis*, 4th ed., McGraw-Hill, N.Y., 1952, p. 319.
(5) Guyot, A., *Chimie & industrie*, **2**, 879, 1167 (1919).
(6) Harding, L., *J. Chem. Soc.*, **119**, 1261 (1921).
(7) Holleman, A. F., and Caland, P., *Ber.*, **44**, 2504 (1911).
(8) McKie, P. V., *J. Chem. Soc.*, **113**, 799 (1918).
(9) Monsanto Chemical Co., *Monsanto Plasticizers*, St. Louis, Mo., 1954.
(10) Monsanto Chemical Co., *Saccharin Monsanto—The Perfect Sweetener*, St. Louis, Mo., 1948.
(11) *Office Tech. Services Rept.*, **PB-70361**, 6854–57 (1948).
(12) *Office Tech. Services Rept.*, **PB-74051**, 405–6 (1947).
(13) Simpson, W. A., and Olsen, J. C., *Ind. Eng. Chem.*, **29**, 1350 (1937).
(14) Suter, C. M., *Organic Chemistry of Sulfur*, Wiley, N.Y., 1944, ch. 3, 4, 5, 6.
(15) U.S. Pat. 1,210,725 (Jan. 2, 1917), D. Tyrer.
(16) U.S. Pat. 1,279,296 (Sept. 17, 1918), C. R. Downs (to Barrett Co.).
(17) U.S. Pat. 1,292,950 (Jan. 28, 1919), J. A. Ambler and H. D. Gibbs.
(18) U.S. Pat. 1,300,227 (April 8, 1919), J. A. Ambler and H. D. Gibbs.
(19) U.S. Pat. 1,301,360 (April 22, 1919), A. Bender.
(20) U.S. Pat. 2,362,612 (Nov. 14, 1944), W. B. Brown (to Allied Chem. & Dye Corp.).
(21) U.S. Pat. 2,540,519 (Feb. 6, 1951), A. D. Green and E. W. Carrier (to Standard Oil Development Co.).

R. W. RADUE
SHIRLEY K. MORSE (Dye Intermediates)

TOLUIDINES, $CH_3C_6H_4NH_2$. See *Aniline*, Vol. **1**, p. 925; *Nitrobenzene and nitrotoluenes*, Vol. **9**, pp. 398, 399, 400.

TOLYLENEDIAMINES, TOLUYLENEDIAMINES, $CH_3C_6H_3(NH_2)_2$. See *Phenylenediamines*, Vol. **10**, p. 379.

2,4-TOLYLENE DIISOCYANATE, $CH_3C_6H_3(NCO)_2$. See *Phosgene (organic isocyanates)*, Vol. **10**, p. 399.

***p*-TOLYL-PERI ACID,** $CH_3C_6H_4NHC_{10}H_6SO_3H$. See *Naphthylamines and naphthylaminesulfonic acids*, Vol. **9**, p. 264.

TONERS. See *Azo dyes*, Vol. **2**, p. 261; *Pigments (organic)*.

TONING. See *Photography*, Vol. **10**, p. 576.

TOOTH PASTE; TOOTH POWDER. See *Dentifrices*, Vol. **4**, pp. 931, 932.

TOPAZ, $Al_2(F,OH)SiO_4$. See *Silica and silicates (mineral)*, Vol. **12**, p. 279.

TORBERNITE, $Cu(UO)_2(PO_4)_4.8–12H_2O$. See *Uranium*.

TOSYLATION

Introduction of a tolylsulfonyl group, $CH_3C_6H_4SO_2$-, specifically the para isomer.

TOTAQUINE. See *Alkaloids*, Vol. **1**, p. 485; *Malaria chemotherapy*, Vol. **8**, p. 663.

TOURMALINE. See *Silica and silicates (mineral)*, Vol. **12**, p. 279.

TOXAPHENE. See *Insecticides*, Vol. **7**, p. 896.

TOXICOLOGY. See *Industrial hygiene and toxicology*.

TOXIFERINES. See *Alkaloids*, Vol. **1**, p. 490; *Stimulants and depressants*, Vol. **13**, p. 39.

TOXINS; TOXOIDS. See *Pharmaceuticals*, Vol. **10**, p. 245; *Serums and serology*; *Vaccines*.

TRACE ELEMENTS. See *Fertilizers*, Vol. **6**, p. 379.

TRACERS. See *Isotopes*, Vol. **8**, p. 100; *Radiochemistry*, Vol. **11**, p. 464.

TRADE-MARKS

A trade-mark is a picture, word, symbol, or other device by which the owner of the mark distinguishes his goods from those of another. Closely allied to trade-marks, which are solely for products, are marks for *services*, marks for *certification* of origin or quality of goods, *collective* marks signifying, for instance, membership in associations or groups, and *slogans*.

Marks meeting all the requirements of the U.S. Patent Office are registrable on the "Principal Register," those meeting only a part of those requirements on the "Supplemental Register" provided the marks have been in use for a year. Trade-marks of all classes that are accepted for registration, both on the Principal Register and the Supplemental Register, are published in the *Official Gazette* of the U.S. Patent Office (see p. 299). (Some states also have trade-mark registration.) Good trade-marks are enforceable whether registered or not; witness the bell of the American Telephone & Telegraph Co., which was used for 32 years and then registered as a service mark only in 1954, after another party sought to register a similar mark for a telephone answering service.

Registration of a trade-mark gives the owner no right he did not have before. Registration on the Principal Register, however, is constructive notice to the public of claim to the ownership of the mark and such registration creates "strong presumption in favor of the validity of the mark" (1).

Trade-marks may be registered for patented or unpatented products and the same mark, if used properly, may be protected for generations.

The chemist, engineer, sales personnel, and executive are concerned chiefly with the following phases of trade-mark law and practice: (*1*) Choice of a mark of greatest sales appeal and enforceability. (*2*) Use of the mark in such manner as to avoid loss of the exclusive right to use it. (*3*) Avoidance of infringement of the trade-marks of others.

For the public, a trade-mark is a "merchandising short cut" to what it wants to buy (2). Consider the case of a high-speed filter aid used in many chemical plants. Without the convenience of trade-marks, the purchaser might specify siliceous remains of marine plankton diatoms of the Miocene period, milled, calcined with x per cent of y flux at z temperature for a hours. Under the trade-mark system, the buyer needs only to order Hyflo or other trade-marked material of his choice.

Such trade-mark specification is not only a short cut but is also flexible. It permits the manufacturer continuously to improve his product, change it so as to give greater value per unit of cost, and extend his line of products with the good will created by previous items. Thus the mark TCP for an additive for gasoline permits the introduction, under the same name, of additives other than the original tricresyl phosphate.

As many as 70–95% of all people buy a wide selection of merchandise by proprietary names, the exact figure varying with the class of goods investigated (3). For gasoline purchasing, for example, the figure is 84%, for toothpaste 89%, and for rubber tires 84%.

Although trade-marks, trade names, and brand names are not identical, many general considerations apply to all such marks or names. A trade-mark applies ordinarily to vendible goods, and a trade name relates to a business and identifies a producer. Other designations of products are often used in the trade as commercial names. These include muriatic acid and oil of vitriol. These names do not fall into any of the classes mentioned, but are sometimes also called "trade names."

DISTINCTION BETWEEN TRADE-MARKS AND PATENTS

Patents (*q.v.*) and trade-marks differ in many regards.

Patents are directed to the substance or structure; trade-marks only to the identification under which goods are sold. Whether Crisco, Spry, and Swiftning are or are not the same hydrogenated vegetable oil shortening is unimportant in connection with trade-marks; the trade-marks are only the names under which the products are sold by different manufacturers. If, on the other hand, there were a broad patent on the product the patent owner would be in position to prevent the manufacture, sale, or use of the hydrogenated oil by competitors, regardless of the name applied to it.

A patent does not exist until granted by the Patent Office. A trade-mark may be good and enforceable without being registered or ever having been filed in the Patent Office. The trade-mark Coppertone is an example of such a common-law trade-mark for a sun tan lotion. The mark was recently upheld and found to be infringed by the mark Copper Tan (4). Registration, however, is very desirable and is nearly universal for the best known trade-marks.

A patent, to be valid, must be applied for within a year of the first commercial use or publication of the invention patented. A trade-mark gains strength by use, even long use, either before or after application for registration in the Patent Office.

A patent, once granted, automatically remains in force, in the absence of adverse action, until its expiration date. A trade-mark, to be kept in force under the new law, requires filing an affidavit of continuing use or satisfactory explanation for its nonuse within twelve months after the end of the fifth year after the original registration.

A patent expires 17 years after its grant and, for all practical purposes, cannot be extended. A trade-mark registration runs for 20 years and is renewable for subsequent, repeated periods of 20 years each.

A patent is freely transferable. A trade-mark is transferable only in connection with the business and good-will formerly associated with the mark.

A patent is subject to license with little or no restriction. A trade-mark may be used by someone other than the owner of the mark only when the owner supervises or otherwise controls the quality of the product of the licensee, so as to preserve the quality that the public has come to associate with the mark.

A patent *creates* the right of an inventor to exclude others from use of his invention for a period of 17 years. A trade-mark registration *recognizes* a right already created through the owner's previous use of the trade-mark.

HISTORY OF TRADE-MARKS

The earliest commercial marks were predominantly pictorial; examples that still survive are white swan, boar's head, and black horse. With the growth in literacy over the years, words, combinations of letters, numbers, or even musical notes came into use, and now constitute a part or the

whole of most present trade-marks, with pictures or special forms of display often included to advantage for attracting attention.

An early use of trade-marks has been authenticated by the excavations at the ancient Roman village of Pompeii. To identify wine from grapes grown in the rich lava soil of the slopes of Mount Vesuvius, the producers of the area placed the mark Vesuvinum on the jars of their wine. Several of the trade-marked jars that were buried under the volcanic ash in the great eruption of A.D. 79 were unearthed about 1700 years later and are on display today.

As early as the 13th century in Italy and only somewhat later in Germany, members of certain guilds were required to place their marks on their handicraft, as an assurance of quality of workmanship.

In England, the mark of the baker on bread was required as early as 1266 (5), the penalty for inferior quality or underweight being placing the baker in a stock in a public place, suspending a faulty loaf from his neck, and pinning his ears back (actually nailing them to the wood of the stock). The use of marks to distinguish traders' goods from those of competitors was common by 1742, and English trade-mark law began in the nineteenth century. The Act of 1883 permitted the registration of trade-marks consisting of "fancy" words, meaning nondescriptive terms. This is still a class of trade-marks permitted over the world, such words now being known usually as "fanciful," this term including invented or coined words.

In the United States, the first trade-mark statute was enacted in 1870. It was held unconstitutional in 1879. Other major acts were passed in 1881, 1905, and 1920. A new, improved, and comprehensive trade-mark act was enacted in 1946. New marks come under the new law. Marks previously registered under the Acts of 1905 and 1920 may be transferred to the more favorable registration under the new law and were so transferred, by reregistrations, to the number of about 30,000 during the first year of operation of the new law. The 1905 and 1920 trade-marks, on expiration of their registrations, are renewable under the new law.

For these reasons, the subject will be here presented on the basis of the Trade-Mark Act of 1946, with reference, however, to many illustrative cases decided under the 1905 and 1920 laws, which are still in effect.

Selection of Trade-Marks

A trade-mark, for commercial reasons, should be easy to read, pronounce, and remember; have an attention-compelling quality; and be free of undersirable connotations. The use of Socony extensively for gasoline has been discontinued partly, it is said, because some motorists hesitated to ask for it for fear of mispronouncing the first "o". The following may be examples of changes made in trade-marks for easier pronounciation: Sitroux tissues to Sitrue, and Baume Bengué to Ben-Gay. A trade-mark including the picture of a baby met with poor response in China until there were added the words "It's a boy." The reader may judge for himself whether Clabber Girl, advertised extensively for a baking powder accessory in the South, creates at first a favorable or unfavorable reaction.

For sales value in advance of extensive advertising promotion, a trade-mark should carry to the user associations of quality or merit or suggest what the product is for or will do.

From the standpoint of law, the mark must be: not confusingly similar to the mark of another for the same goods; outside the category of prohibited marks; and not deceptive, misleading, immoral or scandalous. For registration on the Principal Register, the mark must also be nondescriptive of the goods or of the result of its use. Descriptive marks are registrable on the Supplemental Register and some descriptive

marks on the Principal Register, if they can be shown to have become distinctive for the goods on which used.

When the representatives of the technical and sales staff meet in conference to select the name by which a product will be known in the trade, there is a tendency to propose names or designs that are catchy or cleverly suggestive of quality, composition, or merit for a particular use. Such marks are desirable from the start as trade-marks if they are not descriptive. It is because of the immediate value of such marks that they are frequently found to have been adopted already by others.

Marks Suggestive of Merit or Composition. Examples suggesting merit or use of the trade-marked product are Applikay for a paint to be applied over wallpaper, Lucite for a plastic of exceptional translucency, Nostrip for an additive to prevent stripping of asphalt, and, for a remote control switch for cutting off the sound of commercial announcements on television programs, the mark Blaboff. Standard, initially descriptive, came into use for petroleum products after a pioneeer but far-sighted producer introduced quality standards for the then undependable products of a new industry.

Marks of this general class that have been held to be descriptive and, therefore, not enforceable as trade-marks are Flekdye for a fleck dye, Al-Kol for an alcohol rubbing composition, and Ez-Flo for an insecticide powder. Startgrolay is perhaps a border term, between descriptive and suggestive, for a poultry feed presumably for starting, growing, and laying stock. This combination of three words, which separately may be considered descriptive, into one word has recently been held by a court (6) to be only suggestive and, therefore, permissible as a trade-mark.

Marks suggestive of the *composition* are illustrated by Nichrome for a nickel-chromium alloy, Acrylan for an acrylic fiber, Ethyl for a gasoline containing tetra-ethyl lead, and Chemtan for a synthetic tanning material.

Marks Indicating Producer. Marks which are so well known that they indicate immediately the company which produces and in effect places its reputation behind the products are illustrated by Alcoa, Nabisco, Celanese, GC on the shield of General Chemical, and Du Pont within an oval. Another is Visqueen, a wrapping material of the Visking Company. Prestone is the name chosen for ethylene glycol antifreeze when it was associated with the Presto-O-Lite division of Union Carbide.

Corporate names, even when somewhat shortened by leaving off "Company" or "Inc." have been denied registration in many cases.

Names Established for Other Products. Names that are famous and distinctive for one product should not be chosen ordinarily for other merchandise. Rolls Royce, the well-known mark for an automobile, is not permissible for use by another for radio tubes. Waterman Fountain Pen was able to enjoin the use of Waterman on razor blades, although it might not be able perhaps to prevent its use on merchandise as dissimilar as steam shovels. The law seeks to avoid dilution of the value of a famous mark by its use on even somewhat dissimilar goods of another. There is a present contest over the use on cigars of Johnnie Walker, registered for whisky.

The small producer who does not plan to establish acceptance by extensive advertising is often tempted to adopt a mark of favorable connotation and of present value. Thus a new enterprise may select Cadillac as the trade-mark for electrical appliances, Lincoln for a hammer, and Hercules for a mineral water.

Even large producers or distributors may select marks of desirable long associa-

tion in the public mind. Examples of such association from the days of mythology are Atlas for tires, Trojan for explosives, and Mercury for automobiles.

When the mark is weak and used already on many different producers' goods, the hazard in its selection by an additional producer is less than when the mark is strong. Thus Gold Medal and Blue Ribbon, widely used, may be adopted by another for goods less different than radio tubes from automobiles or razor blades from fountain pens.

Fanciful Words. Invented or coined words, based on no logical derivation, are much less likely than suggestive marks to have been arrived at also by others. Searchers soon learn to expect that marks of obviously logical derivation have been used before.

Examples of fanciful words are Velox for photographic printing paper, Amberlite for ion-exchange resins, and, for skim milk powder, Klim (milk spelled backwards).

Fanciful words that, through misuse in most cases at least, have now become descriptive or generic and are no longer trade-marks are linoleum, dry ice, aspirin, cellophane, and cola, the last representing a class of beverages including material of cola seed.

A word may be fanciful for one product and generic for another. Ivory is fanciful and a good trade-mark for soap but descriptive for elephant tusk.

Portmanteau Words. Portmanteau words as trade-marks are illustrated by the ancient Vesuvinum, formed by collapsing or telescoping the Latin words *Vesuvius* and *vinum*. Trade-marks of this class are Vinsol for the *very insol*uble phenolic fraction of rosin, Santicizer for certain Mon*santo* plast*icizers*, and Nitramon for an explosive containing *nitrate* of am*monia*.

Names of Individuals. Names that are merely surnames are not registrable on the Principal Register. Recently it has been held, however, that the combination of the first name and the last name is not merely a surname. Under this present practice, the complete name of an individual is registrable. Thus Andre Dallioux was accepted whereas J. C. Higgins and Kimberly Clark were held not registrable as being a surname only or a combination of surnames, the latter however winning registration because it had become distinctive of the applicant's goods through long use.

For a discussion of this practice and other subjects relating to developments under the 1946 Trade-Mark Act, see reference (6).

Packages and Configurations. Packages, configurations, and the like are registrable only if capable of distinguishing the goods and then only on the Supplemental Register. Registration of the striped container of the Burgess Battery Company was refused on the ground that it constituted the entire ornamental background of the article and did not serve as a trade-mark (6).

Pictures or Designs. Pictures or designs, either with or without words, are among the most effective trade-marks. The test for distinctiveness being chiefly the appearance, they may be expected also to be more readily registrable and stronger than word marks.

Examples of well-known marks that carry pictures or designs are the bearded men of Smith Brothers' Cough Drops, the Red Cross of Johnson and Johnson, and the Flying Red Horse of Socony Mobil.

Sound Marks. The first sound mark to be registered, No. 523,616 in 1950, was made up of "the musical notes G, E, C played on chimes." The registrant was the National Broadcasting Co., which uses the trade-mark at the beginning of its radio

programs. Gillette has long used musical tones in radio advertising of razors and blades.

Marks with Parts Disclaimed. Marks containing matter in part registrable and in part descriptive are frequently registrable upon disclaiming the descriptive matter as no part of the mark except in the association shown.

Although descriptive or otherwise unregistrable parts of an otherwise registrable mark must be disclaimed before registration on the Principal Register, the law on this point has not yet been interpreted for Supplemental Register marks (6).

Secondary Meaning Words. Paris, Gold Coast, and Scotch are examples of geographical names that have been registered for many products after having first acquired secondary significance by long use in trade. Names of little known places such as Mulhall or Purcell may be assumed to be registrable even in the absence of previous establishment of such secondary meanings.

Misspellings and Translation. Misspellings or colloquialisms, such as Ruberoid for rubberoid or Bama for Alabama, do not, in the absence of having acquired secondary meanings, avoid the objection to otherwise unacceptable marks (9). Uneeda, although an excellent trade-mark, was originally equivalent to "You Need A."

Translations into foreign languages are equivalent to English terms. "Forbidden Love" has been held confusingly similar to "Le Fruit Defendu."

Strong versus Weak Marks. Unless there is some very special and certain advantage in choosing an initially weak mark such as "Premier" or "Blue Ribbon," it is desirable to select a strong mark such as "Kodak" that does not depend upon long use to make it distinctive of the owner's product. In fact a mark judged to be highly descriptive can never become distinctive under the law. The choice of a strong mark is particularly desirable in view of the rather strict requirements for acquiring secondary significance by a trade-mark initially weak.

As pointed out by Derenberg (6), registration based on such secondary meaning has been recently denied to a number of marks in spite of their 5 years of substantially exclusive use. Thus "Butter Nut" as applied to candy was held incapable of distinguishing the goods. The mark was said to be descriptive if applied to candy containing butternuts, and misdescriptive if applied to candy not containing butternuts. "Prefab" as applied to shelving material was held to be descriptive. The Shredded Wheat case (10) long ago established the law that, regardless of how long a claimant may have fortuitously enjoyed the exclusive use of a mark, he cannot appropriate the mark for his sole use if the mark is merely and clearly descriptive.

There is another great advantage in a strong trade-mark over a weak mark. With a mark as strong (characteristic) as Kodak, for example, there would be reluctance on the part of a court to permit its use by another not only on the same or similar merchandise but also on merchandise considerably removed from the camera class. Thus the use of Kodak on a bicycle if poorly made might reflect upon or "dilute" in the public mind the value of Kodak on its own limited class of products. "Premier," on the other hand, might be permitted on goods relatively close to mayonnaise or other goods for which registered.

Illinois, Massachusetts, and New York now have state laws against dilution. The antidilution principle has long been a feature of federal practice.

Confusing Similarity to Other Marks. A trade-mark that so resembles another as to be likely to cause confusion or mistake or to deceive purchasers will be refused registration by the Patent Office. On the basis of confusing similarity, owners of

marks may oppose the registration of a mark on the Principal Register, such opposition to be filed during the 30-day period following publication of the mark in the *Official Gazette*.

It is good policy to adopt no mark that is on the border line between being and not being confusingly similar to another. Even though good but misdirected prosecution by the attorney may bring registration of the mark in the Patent Office, continued use of such mark may later be held to be an infringement on the similar mark.

Similarity preventing registration in the first place or leading to possible infringement later may reside in likeness of (*1*) sound of the marks when spoken, (*2*) spelling, (*3*) appearance, (*4*) association of ideas as in the case of Gate-House and Toll House, or (*5*) cadence or lilt as in the instance of Lorodo and Yodora.

Now there is a tendency of the Court of Customs and Patent Appeals to recognize registrability when a mark, although similar in one or more regards such as sound or appearance, is not merely descriptive and shows considerable dissimilarity of meaning (6). Thus "Surge" was recently registered for detergent compositions over "Surf" for the same kind of product. Coined words, having no meaning, obviously cannot be distinguished by any difference of meaning.

Illustrating marks that have been held to be confusingly similar are the following: Micronized to Micronex; composite mark dominated by EMI to AMI; Zac-Lac to Jap-A-Lac.

It has been held, on the other hand, that Spic is not confusingly similar to Spry, Oaties to Wheaties, or Rustaboo (for a rust-preventive treatment) to Tabu or Taboo.

Form of Display of Mark. If the decisions as to confusing similarity seem in some instances to be themselves confusing or inconsistent, it is to be remembered that marks may differ in style of label, shape, size, format, color, and pictures. All these factors bear on the likelihood of confusion in actual use of the mark. The purchaser of small items acts quickly and upon impression. He depends on a casual glance. Yan-Cola was refused registration not only because of including the word "Cola" but also because of script and color arrangement considered likely to cause confusion with Coca-Cola. When marks are without doubt confusingly similar, then the other factors are not sufficient to provide distinction.

Kind of Merchandise. Since the same mark may be used by different persons on different kinds but not on the same kind of goods, there remains the question as to what goods are of the same kind.

The use of the mark V-8 on vitamins was held to be an infringement of the same mark owned by another for use on vegetable juice cocktail (11).

The Ford Motor Company was able to prevent the use of the trade-mark Ford on an insecticide of another company. The court held insecticides to be merchandise of the same descriptive properties as fertilizer and other agricultural supplies to which the motor company had long affixed the name Ford. The defendant company was not helped in this action by having among its stockholders a man by the name of Ford or by using script for the trade-mark instead of the block letters of the motor company. Any implication of the defendant that he did not seek to mislead the public as to the source of the goods was negatived by prominent and conspicuous reference in his advertising literature to a birthday party for Mr. Henry Ford (12). Another factor, no doubt, was the fact that the mark "Ford" is a strong one.

Other decisions on similarity of goods are summarized in part below, decisions that may be assumed to have depended in part on the weakness or strength of the marks.

Cosmetic hand cream is not the same kind of goods as an emulsion of medicinal oil for internal lubrication. Goods sold even to the same customers and over the same counters may sometimes be distinguished, as in this case, by difference of uses and structures of the products sold (13).

Beer and wine are closely related and the mark for one may not be registered by another party for use on the other beverage.

Automobile polish and ready-mixed paint are so closely related that the trade-mark for one may not be registered by a different person for the other (14).

Candy and oleomargarine are different classes of merchandise (15).

Requirements for Registration of Trade-Marks

Principal Register. No mark by which the goods of an applicant may be distinguished from the goods of others, Sec. 2 of the Trade-Mark Act of 1946 says, will be refused registration on the Principal Register on account of its nature unless it

(a) Consists of or comprises immoral, deceptive, or scandalous matter; or matter which may disparage or falsely suggest a connection with persons, living or dead, institutions, beliefs, or national symbols, or bring them into contempt or disrepute.

(b) Consists of or comprises the flag or coat of arms or other insignia of the United States, or of any State or municipality, or of any foreign nation, or any simulation thereof.

(c) Consists of or comprises a name, portrait, or signature identifying a particular living individual except by his written consent, or the name, signature, or portrait of a deceased President during the life of his widow, if any, except by the written consent of the widow.

(d) Consists of or comprises a mark which so resembles a mark registered in the Patent Office or a mark or trade name previously used in the United States by another and not abandoned, as to be likely, when applied to the goods of the applicant, to cause confusion or mistake or to deceive purchasers.

(e) Consists of a mark which, (*1*) when applied to the goods of the applicant is merely descriptive or deceptively misdescriptive of them, or (*2*) when applied to the goods of the applicant is primarily geographically descriptive or deceptively misdescriptive of them, except as indications of regional origin may be registrable under section 4 hereof, or (*3*) is primarily merely a surname.

(f) Except as expressly excluded in paragraphs (a), (b), (c), and (d) above, nothing herein shall prevent the registration of a mark used by the applicant which has become distinctive of the applicant's goods in commerce. The Commissioner may accept as prima facie evidence that the mark has become distinctive, as applied to the applicant's goods in commerce, proof of substantially exclusive and continuous use thereof as a mark by the applicant in commerce for the five years next preceding the date of the filing of the application for its registration (16).

Section 2 (f) above shows particularly how secondary meanings arise through use of marks. A mark that is merely descriptive, however, cannot become distinctive through use and cannot, therefore, become acceptable for registration on the Principal Register except when adequate proof has been submitted that the public has accepted the mark as distinctive in fact.

Supplemental Register. For the purposes of registration on the Supplemental Register, a mark must have been in lawful use for a year preceding the date of filing of the application. The mark may be descriptive. It may consist of a trade-mark, symbol, label, package, configuration of goods, a surname only or whole name, word, slogan, phrase, surname except the name of a person without his consent, geographical name, numeral, or device or any combination of any of the foregoing, provided the mark is capable of distinguishing the applicant's goods or services and is not forbidden by paragraphs (a), (b), (c), or (d) of Section 2 above (17).

Upon a proper showing by the applicant that he has begun the lawful use of his

mark in foreign commerce and that he requires domestic registration as a basis for foreign protection of his mark, the Commissioner may waive the requirement of a full year's use and may grant registration forthwith.

The requirement of a year's use, before filing for registration on the Supplemental Register, is frequently met as follows: File for registration on the Principal Register. When the registration is refused, transfer the application to the Supplemental Register. By that time a year of use will have passed in many cases.

A mark registered on the Supplemental Register is not precluded by that condition from being registered later on the Principal Register. In many cases, such transfer is desirable after five years of use of the mark in such manner as to make it distinctive of the owner's goods, the transfer being made under the provision that acquiring "secondary meaning" under Section 2 (f) entitles a mark to admission to the Principal Register.

Disadvantages of Supplemental Register. Registration on the Supplemental Register, although permissible for many marks not eligible for the Principal Register, is subject to a number of limitations on the value of the registration. Supplemental Register marks are not prima facie evidence of the registrant's ownership, are not constructive notice of the registrant's claim of ownership, do not become incontestable after five years of use, may be cancelled at any time on the showing of any person that he is being or will be damaged, may not be involved in interference, and may not be filed in the Treasury Department to stop importations (18).

These disadvantages of the Supplemental Register do not apply if the mark is later placed on the Principal Register.

Kind of Marks

Another provision of the law common in part to both Principal and Supplemental registers relates to the various kinds of marks (19). The marks are as follows, with certain comments and some examples added.

1. Trade-marks, including any word, name, symbol, or device adopted and used by a manufacturer or merchant to identify his goods and distinguish them from those manufactured or sold by others. (These marks are for tangible products only.)

2. Service marks such as marks, names, symbols, titles, slogans, and like distinctive features of radio or other commercial advertising. The Bell telephone trade-mark is an example.

3. Collective marks, as, for instance, marks to indicate membership in a union, cooperative, association, or other organization. Examples are the shield with "ACS" for the American Chemical Society and "EXT-DFPA" for the Douglas Fir Plywood Association.

4. Certification marks used by one or more persons other than the owner of the mark, to certify regional or other origin, material, mode of manufacture, quality, accuracy or other characteristics of goods or services or that the work on the goods or services was performed by members of a union or other organization. An example is "Sanforized" for a fabric treatment applied by an approved group of preshrinkers of the fabric.

Whenever applicable, the provisions for registered trade-marks relate also to unregistered or common law trade-marks and to the other forms of marks.

Service Marks. Service marks, first authorized under the 1946 Act, are for serv-

ices of an intangible nature, not goods. A mark such as "The Music You Want When You Want It" of RCA applies to the records to be sold rather than an intangible service. Its registration was denied (6).

Furthermore the services for which marks may be registered must enter into interstate commerce. The service given in a hotel, in a single location, for instance, would not be considered as entering into commerce. Registration of "Lubricheck" by The Standard Oil Co. of Ohio, for certain services rendered by automobile service stations, was refused registration because it was held that the service was only intrastate (20) (in Ohio).

Service marks registered by the Patent Office in 1954 include the following illustrative examples: "helena rubinstein" for hair dressing and dyeing services and beauty culture; "Fir" for marketing research; "Pyresote" for chemically treating lumber, etc.

Slogans. Among the important new classes of marks established by the 1946 Act are slogans. Well-known slogans, registered or unregistered, are: "Every Form of Chemical Service," of Foster D. Snell, Inc.; "At General Electric Progress Is Our Most Important Product"; "Happy Motoring Starts at the Esso Sign"; and "The Fate of a Fabric Hangs by a Thread" of American Enka.

This last slogan, after a long contest, has been accepted on the Principal Register. Registration was first denied by the Patent Office but finally granted on order of the District Court to which appeal had been taken. In later decisions (7) the Patent Office has declined to follow this court decision as controlling; the slogan in the Enka case, it is said, was not a sufficiently conspicuous part of the composite mark to make registrability of the slogan itself the sole deciding factor. Since the Enka decision, the Patent Office has denied registration even on the Supplemental Register to "Best in the Long Run" for tires, "The Best and Biggest Cigar," and "America's Most Luxurious Mattress."

A slogan, even for the Supplemental Register, requires some potential distinctiveness and an element of originality or uniqueness. Phrases that are merely informative or laudatory do not meet the requirements for the Principal Register, an example being Robert Hall Clothiers' "Why pay for overhead when you can't wear it," its registration on the Principal Register having been denied. A slogan for feed products held to meet the requirements for registration, partly because of being "catchy and rhythmic," is "Definite Feeds for Definite Needs" (6).

Application for Trade-Mark Registration

The application for trade-mark registration includes a written statement of the kind of goods or items on which the mark is to be used; the date of the first use on any one of the items; the date of such first use in commerce subject to regulation by Congress, as among the states; a drawing of the mark as applied to the goods; five specimens of the mark, such as labels or photographs of the mark on the goods; and the filing fee of $25.00 for each Patent Office Class of merchandise (usually only one class) within which the various items fall.

The application may be made by an individual, a firm, or a corporation. It is executed by the owner of the mark, that is, by the user of it, not by the one who conceived of it or first proposed its use.

The responsibility of the executive, in connection with the application, includes providing five copies, with extras for the files, of specimens (facsimiles, printed labels,

photographs of stencil applications, or other forms) showing the mark as actually applied to the goods. If the mark is applied by means of a label, the label (modified in this instance to illustrate the text) may be of the style usual for the owner and include such information as the following:

LAMINAC
trade-mark
Polyester Resin
American Cyanamid Co.,
New York

Care is taken to omit "registered" in connection with the "trade-mark" on the labels filed with the application because the mark is not registered at the time the application is filed. Labels for meat products and alcoholic liquors must be approved in advance by the Department of Agriculture and the Bureau of Internal Revenue, respectively.

The date of first use may be omitted when the registration is filed under the "Convention" (within 6 months of the first foreign filing) or when the mark has been registered abroad and a certified copy of the foreign registration is included.

For registration on the Supplemental Register, it is necessary also to certify that the mark has been in lawful use by the applicant for the year preceding the application for the registration.

A drawing is required. This is made to advantage by the professional patent or trade-mark draftsman. The drawing shows the mark as used on the label and also the name of the owner.

Recital of Class of Merchandise. The point requiring the most consideration, once the mark has been selected, is usually the description of the merchandise for which the mark is to be protected. Although it is not difficult ordinarily to select the general class of the goods in accordance with the major classes established by the Patent Office, the choice of the particular species of merchandise within the broad class requires great care. For a material within "Class 6, Chemicals and Chemical Compositions," definition of the species, for instance, as "dyes" would exclude the registrant, in the absence of an additional registration, from the sole right to use the mark on merchandise other than dyes or closely related materials.

The present practice is to present a list of merchandise, within one main class, to which the mark has been applied and for which registration is sought.

The classes of goods and services established by the Patent Office are shown in Table I.

Actions and Amendments. Ordinarily the Patent Office sends to the applicant several letters or actions before the mark is either accepted for publication or finally rejected.

Response to each action must be made within 6 months. The response (amendment) relates usually to formalities, changes in the description of the goods to make the description either more definite or more restricted, disclaiming parts of marks except in the association shown, or the questions of descriptiveness of the mark or confusing similarity to a mark previously used by another.

Appeal may be made to the Commissioner of Patents on final action by an Examiner adverse to the applicant for registration and from the Commissioner to the Court of Customs and Patent Appeals or to the District of Columbia District Court.

TABLE I. Classification of Goods and Services.

Class no.	Title	Class no.	Title
	Classification of Goods		
1	Raw or partly prepared materials	26	Measuring and scientific appliances
2	Receptacles	27	Horological instruments
3	Baggage, animal equipments, portfolios, and pocketbooks	28	Jewelry and precious-metal ware
4	Abrasives and polishing materials	29	Brooms, brushes, and dusters
5	Adhesives	30	Crockery, earthenware, and porcelain
6	Chemicals and chemical compositions	31	Filters and refrigerators
7	Cordage	32	Furniture and upholstery
8	Smokers' articles not including tobacco products	33	Glassware
9	Explosives, firearms, equipments, and projectiles	34	Heating, lighting, and ventilating apparatus
10	Fertilizers	35	Belting, hose, machinery packing, and nonmetallic tires
11	Inks and inking materials	36	Musical instruments and supplies
12	Construction materials	37	Paper and stationery
13	Hardware and plumbing and steam-fitting supplies	38	Prints and publications
14	Metals and metal castings and forgings	39	Clothing
15	Oils and greases	40	Fancy goods, furnishings, and notions
16	Protective and decorative coatings	41	Canes, parasols, and umbrellas
17	Tobacco products	42	Knitted, netted and textile fabrics and substitutes therefor
18	Medicines and pharmaceutical preparations	43	Thread and yarn
19	Vehicles	44	Dental, medical, and surgical appliances
20	Linoleum and oiled cloth	45	Soft drinks and carbonated waters
21	Electrical apparatus, machines, and supplies	46	Foods and ingredients of foods
22	Games, toys, and sporting goods	47	Wines
23	Cutlery, machinery, and tools, and parts thereof	48	Malt beverages and liquors
24	Laundry appliances and machines	49	Distilled alcoholic liquors
25	Locks and safes	50	Merchandise not otherwise classified
		51	Cosmetics and toilet preparations
		52	Detergents and soaps
	Classification of Services		
100	Miscellaneous	104	Communication
101	Advertising and business	105	Transportation and storage
102	Insurance and financial	106	Material treatment
103	Construction and repair	107	Education and entertainment

Government Fees. Filing fee $25.00.

Claiming the benefit of the new law for a mark previously filed under an old law, $10.00.

Title report to accompany the request for bringing the old trade-mark under the new law, $1.00.

Publication or final registration of the mark, none.

Filing (*a*) an opposition to the registration of a trade-mark, (*b*) petition for cancellation, (*c*) application for renewal of registration of a mark for each class of goods for which wanted, or (*d*) appeal to the Commissioner of Patents from an action of an Examiner, $25.00 each.

For certificate of correction of registrant's mistake, $10.00.

For copy of trade-mark, $0.10.

For a complete statement of the many fees, see the statute (23) and Patent Office Rule 2.1.

Publication, Opposition, and Interference

When it appears to the Patent Office, more particularly to the Trade-Mark Examiner, that the trade-mark is acceptable for registration, the mark is published in the *Official Gazette*. This is notice to the public of the impending registration.

When the mark is one for the Principal Register, an opposition may be filed within thirty days of the date of publication by one who believes that he would be damaged by the registration, for example, by one who owns a mark to which, he alleges, the proposed mark for the same class of goods is confusingly similar. The burden of proof is on the opposer.

Oppositions, if prosecuted to a conclusion through the Patent Office, involve arguments as to the validity of the allegations made by the opposer and sometimes the taking of testimony.

In most instances, the possibility of a settlement of the opposition should be explored. It is possible in some cases to convince the opposer that the two marks are so distinguished as to avoid confusion to the public, in other cases that the goods or services to which the marks are applied are so different that confusion will not arise. Perhaps even more often, the applicant for the new registration settles on the basis of an agreement to restrict his use of the mark in some manner to avoid confusion. Thus, the applicant may restrict his use of the mark to goods only for one industry or sale in one kind of store, only in the form of a solution, or in some other manner to distinguish the goods clearly from those of the owner of the registered mark.

In the absence of a settlement and in the case of probable confusion between the marks of the applicant and the opposer, for the same merchandise, the applicant ordinarily should consider selecting another mark and abandoning his application for registration. It should be recognized, however, that there is a new trend towards somewhat greater liberality in registering marks over those of opposers (6).

Marks published for registration on the Supplemental Register are not subject to opposition. For such Supplemental Register marks, one who considers the registration damaging to him may institute a cancellation proceeding (see p. 296).

Interferences may be declared between two or more applications for registrations of similar marks or between an application and a registration. No interference will be declared, however, between an application and a registration that has become incontestable under the five year provision. Early filing of the application for registration is an advantage when the application becomes involved in interference proceedings.

Concurrent Registrations of Mark. Concurrent registrations of the same or similar marks by two or more applicants are permitted (24). For such concurrent registrations it is required (*a*) that the applicants shall have used the marks at the

same time and lawfully prior to the filing date of any applicant for the registration and (*b*) that the Commissioner of Patents or a court on appeal shall have determined that the continued use of the mark will not result in confusion, mistake, or deceit of purchasers. Use of the mark by two or more parties in different territories is a usual basis for concurrent registration.

Marking Trade-Marked Goods

The trade-mark owner should apply to his mark as used the words "Registered in U.S. Patent Office," "Reg. U.S. Pat. Off." or the letter "R" enclosed within a circle (25). A suitable form of label after the mark is registered would be the following:

Cellosolve ®
Ethylene Glycol Monoethyl Ether
Carbide & Carbon Chemicals Co.
New York

Such marking in the statutory form shows at once the intent to use the mark as a trade-mark and not in the descriptive or generic sense. On each label and on each piece of advertising or other literature utilizing the trade-mark, the fact that the mark is a trade-mark should be shown. In place of one of the indicia above, some trade-mark owners will sometimes place an asterisk(*) after the mark, with reference at the bottom of the page to the status as a trade-mark.

When the mark is not registered, the notice should be simply "trade-mark."

Marking is not only notice to the public but also a reminder to the owner that he should present the mark as a trade-mark and not use it as the description of the goods.

Failure to show in legal form that the mark is registered will prevent the plaintiff, in a suit for infringement, from recovering profits or damages except for infringement continuing after actual notice of registration, as by letter.

Trade-marks may be affixed in various manners provided the marks are visible to the buyer at the time of purchasing. A lens, however, is not properly marked when the mark is affixed to the camera and not to the lens (26).

For a packet of playing cards, it has been held that the mark must be on the outside, so as to be visible to the buyer before he selects the goods. A decorated ace card inside the packet does not suffice. The owner's name need not appear on the label carrying the trade-mark. The public buys by the mark, without the need of identifying the maker by his specific name or place of manufacture. A maker of tooth brushes omitted his name from the mark for his second-quality product. The trade-mark without the name was held sufficient (27). It is good practice under most circumstances, however, to include the owner's name.

When two marks are separately applied to the same goods, there is *infringement* in the use of either or both marks by another party. In the case of a large power-driven machine, the name Kelly was imprinted on the moving ram and the word Gemco on a side panel. The application of the two marks, it was held, does not give to another the right to use either mark alone (28).

False marking to misrepresent origin or description is illegal. Any person believing himself to be damaged or likely to be damaged by such marking may institute civil action against the one who, by the false marking, misrepresents the goods or services or their origin (29).

Imports. Importation of goods falsely marked with copy or simulation of a trade-mark on the Principal Register is prohibited.

Importation of goods bearing a Principal Register trade-mark, the importation being without the consent of the owner of the mark, is prohibited under the tariff law. For this reason, tourists returning to the United States are commonly advised before arrival to obliterate the trade-marks on goods purchased abroad, such as "Chanel No. 5" on a popular perfume.

Loss of Trade-Mark

In connection with a registered mark, the executive should avoid use of the mark in a descriptive manner, avoid non-use of the mark for two consecutive years with intent not to resume, and make certain the required affidavit to facts showing continuing use is filed within twelve months after the end of the fifth year of registration of the mark (30). In this affidavit, he may seek also recognition of incontestability of the mark.

Misuse of Mark. A mark on the Principal Register may be cancelled at any time "if the registered mark becomes the common descriptive name of an article or substance on which the patent has expired, or if the registered mark has been assigned (outright transfer of title) and is being used by, or with the permission of, the assignee so as to misrepresent the source of the goods or services in connection with which the mark is used" (31).

Loss of trade-mark rights due to use of the mark as a descriptive term is well illustrated in the Cellophane case (32).

The circumstances bearing on the question whether the term cellophane had become descriptive included the following: Cellophane initially was nondescriptive and a good trade-mark. Over a period of years, the mark was used in many instances, however, in what was held to be descriptive manner. In an affidavit supporting the application for registration of the trade-mark, the President of the Du Pont Cellophane Company used the term "cellophane" spelled with a small "c." The articles of incorporation of the Du Pont Cellophane Company gave as one of the objects the manufacture and trade in "cellophane, transparent wrapping material, viscose products," etc. Later the *Du Pont Magazine* referred to the "manufacture of cellophane." Emphasis in advertising literature was placed upon "Du Pont Cellophane" enclosed in an oval as a designation of the Du Pont material. A survey of retail dealers in cellophane products by the defendant indicated that 88% of them knew no other name than cellophane by which they might order the particular article.

Considering all the circumstances, the Court held that the course of conduct of the owner of the mark and particularly its "advertising campaign tended to make cellophane a generic term descriptive of the product rather than its origin." The court held also that the expiration of the patents on the manufacturing processes terminated any right Du Pont had to the exclusive use of the word cellophane insofar as it had become merely descriptive of the product itself.

The trade-mark "Aspirin" was cancelled on even less conclusive evidence that the the term had become a common noun.

In view of the decision in these cases and others along the same line, it is obvious that care must be taken to avoid the use of a trade-mark as the means of describing the product and particularly to avoid the use of the trade-mark in lieu of a commonly accepted descriptive name.

The exercise of caution to avoid misuse of trade-marks as descriptive terms is evident. The producers of a new cheese chose the mark "Liederkranz" but wisely used, in the next line of their label, "Brand soft ripening cheese." In this way they gave the public means, other than the trade-mark, for identifying the product. A similar precaution with Cellophane would have involved use of some such accompany-

ing line as "Brand of transparent cellulose sheeting." When Duprene first appeared as a mark for a synthetic rubber some years ago, the owners of the mark quickly encouraged public use of another name, "neoprene," so that "Duprene" would not be the only term for designating the new product. Duprene is still a registered trade-mark. Long before that time, the advertising suggestion "Picture Ahead—Kodak as You Go" disappeared from highway billboards after brief use, presumably when the possible hazard in using a trade-mark as a verb was recognized. A 1954 publication shows the care now used by the former owners of the Cellophane trade-mark in providing descriptive terms other than trade-marks to describe their products; the publication refers to certain new products as Dacron polyester fiber and Mylar polyester film. The long life of a mark used correctly is illustrated by the trade-mark Vaseline, the registered trade-mark of Chesebrough Manufacturing Company Consolidated. This mark is used on products of this company, the best-known product being petroleum jelly.

Abandonment. A trade-mark becomes abandoned when its use is discontinued with intent not to resume. Discontinuance of use for two years is prima facie evidence of such intent, that is, proof in the absence of controverting evidence.

A trade-mark becomes abandoned also when the registrant uses the mark in such manner as to cause it to lose its significance as an indication of the origin of the goods (32), as shown in the Cellophane case. A trade-mark becomes abandoned when it is transferred to another without transfer of the good will of the business or that part of the business to which the mark relates (34). Abandonment of a registered mark results, also, from licensing a mark without provision for control, by the owner of the mark, of the quality of the goods to which the mark is applied. A license is a grant of the right to use the trade-mark without transfer of the title. Thus it differs from an assignment (see p. 295). A naked license constitutes an abandonment. In one instance, the owner of the registered mark issued a license, without the proper reservations, for use of the mark in a territory in which the owner was not operating. This was the territory north of the Ohio River. The court held that this act caused abandonment of the mark in this territory. The act did not affect the standing of the mark in other parts of the United States (35). Retention of the right to use the mark by the one who issues the license is persuasive under some circumstances of intent not to abandon the mark (36).

Cancellation of Registration. Cancellation proceedings may be instituted by any person who believes he may be damaged by the registration of a trade-mark.

For marks on the Supplemental Register, the application for cancellation may be made at any time. The application for cancellation may be based on an allegation that the registrant was not entitled to register the mark at the time of his application for the registration of it, that the mark is not used by the registrant, or that the mark has been abandoned.

Marks on the Principal Register, although incontestable on most grounds after five years, may be cancelled

(*a*) Within five years from the date of registration of the mark; or

(*b*) At any time that the mark becomes the common descriptive name of an article or substance upon which the patent has expired or the mark has become abandoned;

(*c*) At any time that it can be shown that the mark was obtained by fraud, is of class not permissible under the law, or is being used with the permission of the owner to misrepresent the source of the goods or services to which the mark is applied; or

(*d*) At any time in the case of a certification mark on the ground that the registrant (*1*) does not

control, or is not able legitimately to exercise control over, the use of such mark, or (*2*) engages in the production or marketing of any goods or services to which the mark is applied, or (*3*) permits the use of such mark for other purposes than as a certification mark, or (*4*) discriminately refuses to certify the goods or services of any person who maintains the standards of conditions which such mark certifies (37).

The Federal Trade Commission, on its own initiative, may apply for cancellation of a trade-mark registration on the Principal Register, on any of the grounds specified in sections (*b*), (*c*), and (*d*) above.

Original Trade-Marks on Reconditioned Goods. The question whether the original trade-mark may be applied to reconditioned or repackaged goods may arise at any time.

Automobiles, for instance, are frequently used and then resold under their original names. The Supreme Court has considered such practice in the case of spark plugs without disapproval (38).

Rebottling a trade-marked perfume and reselling the rebottled material in smaller packages, under the original mark, was also held by the Supreme Court to be permissible under circumstances considered not to deceive the public (39).

In a 1954 decision, the District Court in Los Angeles enjoined closely related practice. The defendant was dispensing leading brands of perfumes in small vials and providing, it was said, no assurance of their authenticity or strength.

Validity

Whether a mark is descriptive or only suggestive is a frequent question in validity cases. "Validity of a mark ends where suggestion ends and description begins," says Judge Learned Hand.

Registration on the Principal Register, however, is *prima facie* evidence of the validity of the registration, of registrant's ownership of the mark, and of registrant's exclusive right to use the mark in commerce in connection with the goods or services specified in the registration. It creates a strong presumption of validity of the mark (1).

For a trade-mark already on the Principal Register of the Patent Office the "constructive notice" prevents registration of the mark on a state register by a possible competitor in any state, regardless of whether the mark has or has not been used in commerce in that state.

Infringement

Infringement of a trade-mark arises from using without the consent of the registrant any reproduction, counterfeit, copy, or colorable imitation of any registered mark in connection with the sale, offering for sale, or advertising of any goods or services on or in connection with which such use as is likely to cause confusion or mistake or to deceive purchasers as to the source of origin of such goods or services (40).

In a suit for infringement, the alleged infringer may use the same defenses against infringement of a registered mark as would be available to him if the mark were not registered (41).

No trader may adopt a trade-mark so resembling that of another trader that ordinary purchasers, buying with ordinary caution, are likely to be misled (42).

Newspapers, magazines and like periodicals are not liable for damages in the un-

witting infringing use of a trade-mark. They are liable only if they continue to use the mark in an infringing manner after the infringement has been called to their attention and after such time following the notice as may be necessary to avoid unreasonable delay in delivery of the periodicals.

When the decision as to confusing similarity between marks is a close one, much dependence may be placed on the record of instances or absence of instances in which the public has actually bought the merchandise of the alleged infringer in the belief that it was the merchandise of the trade-mark owner.

The selection of a mark with the intent to palm off wares as those of another is strong evidence of the likelihood of confusion (43). See p. 286.

The defenses that may be used against trade-mark infringement are briefly as follows: (*1*) Fraud in obtaining registration or establishing the incontestability of the mark. (*2*) Abandonment of the mark. (*3*) Assignment of the mark or misuse in manner to misrepresent the source of the trade-marked goods or services. (*4*) Descriptiveness of the mark. (*5*) The defendant's use of the mark antedates that of the registrant and has been continuous from a date preceding the publication of the registered mark in the Official Gazette. (*6*) The mark is being used in manner to violate the antitrust laws (44).

When infringement is established, the court, first of all, will issue an injunction against continuance of the infringement.

Measure of Liability for Infringement. The owner of a registered trade-mark is entitled to recover (*1*) defendant's profits from the infringement, (*2*) any damages sustained by the owner, and (*3*) court costs of the action to prove the infringement (45).

In assessing profits, the trade-mark owner needs to prove only the amount of sales of the infringer; all elements of costs, which the infringer claims as deductions from sales in the calculations of profits, must be proved by the infringer.

The measure of damages is stated in a recent 2nd Circuit Court case (1) to be what the trade-mark owner would have received if allowed to sell his product without the sale of the product by the infringer. The assessment of increased damages, up to three times the actual finding in extreme cases, is discretionary with the court (45) and is not common.

In those cases in which notice of registration is not attached to the mark as used, damages are recoverable only for infringing acts that occur after notice of infringement is given to the offending party.

When the suit is for unfair competition, on the other hand, then the trade-mark requirement as to notice of registration of the mark does not apply.

Foreign Trade-Marks

The nationals of countries adhering to the International Convention (an agreement for the protection of industrial property) may register in the United States only marks that have been registered previously by them in their own countries or are alleged to be in use in commerce (44). When an application is filed in any Convention country within 6 months of the date of the first filing in a Convention country, the applicant may claim the first filing date as the effective date for the other filing.

In many countries registrations by foreign nationals are not permitted before home registration is completed. In advance of registration in the U.S., for instance, a U.S.

citizen would not be allowed to complete registration of his trade-mark in those countries. This law, however, is no longer in force in Austria, Denmark, Germany, Norway, Sweden, and Switzerland (46). Belgium has an even more strict requirement: a registration in Belgium is invalid if the foreign registrant did not complete home registration before filing the application for registration in Belgium (47).

There is a disadvantage, on the other hand, in extensive use of a trade-mark before applying for registration abroad. This is the danger of piracy of the mark by another. The mark in a foreign country belongs to the one who first uses it or first registers it there, not to the one who has made it valuable by use in some other country.

In the foreign market trade-marks are particularly important. Often they are the only means of identifying the quality of the products in the public mind. The foreign buyer relies upon his previous successful experience with a product. He cannot rely upon the reputation of an unknown producer in a distant land.

Literature of Trade-Marks

Selected publications are the following:

Patent Office, *Rules of Practice in Trade-Mark Cases.* U.S. Govt. Printing Office, Washington. $0.35. This publication includes not only the Patent Office Rules but also the 1946 Trade-Mark Statute.

U.S. Patent Office Gazette, published weekly by the Patent Office. $35.00 a year. The trade-mark section of the *Official Gazette* is now separated from the patent section and appears as the second section. It is possible to subscribe separately to the trade-mark section. It lists all marks accepted subject to opposition or actually registered. Both those on the Principal and those on the Supplemental Register are listed.

Search Room for Trade-Marks in the Patent Office. Here all trade-mark registrations are classified in several ways—alphabetically; by class such as geographical, historical, etc.; and by assignee. Qualified assistants are at hand to help the uninitiated.

Small Business and Trade-Marks, Department of Commerce. U.S. Govt. Printing Office, 1949.

U.S. Patents Quarterly (abbreviated *P.Q.* or *U.S.P.Q.*), published weekly and in bound form quarterly by The Bureau of National Affairs, Washington. It contains copies of decisions of the courts and Patent Office in patent, trade-mark and copyright cases.

The Trade-Mark Reporter, published monthly by U.S. Trade-Mark Association, New York.

Journal of the Patent Office Society, published monthly by the Patent Office Society, P.O. Box 685, Washington. This journal, edited and managed by the members of the staff of the Patent Office, contains timely discussions of patent and trade-mark matters.

Callmann, Rudolf, *The Law of Unfair Competition and Trademarks.* 2nd ed., Callaghan and Co., Chicago, 1950. 5 vols.

Daphne Robert (Mrs. Robert W. Leeds, now Assistant Commissioner of Patents), *The New Trade-Mark Manual.* Bureau of National Affairs, Washington. 1947.

Derenberg, W. J., *Trade-Mark Protection and Unfair Trading.* Matthew Bender, Albany. 1938. *The Sixth Year of the Lanham Trade-Mark Act of 1946.* Bureau of National Affairs, Washington. 1953.

Hinline, H. D., *Forms and Their Use in Patent and Trade-Mark Practice.* Michie, Charlottesville, Virginia, 1951.

Ladas, S. P., *International Production of Industrial Property.* Harvard Univ., 1930. Also articles on foreign trade-marks.

Rogers, E. S., *Good Will Trade-Marks and Unfair Trading.* A. W. Shaw. 1914. Still an excellent book for general reading.

Rogers, E. S., *Trade-Marks in Transition*, Vol. 14, No. 2 of *Law and Contemporary Problems.* Duke Univ., 1949.

Zimmerman, O. T., and Lavine, I., *Handbook of Material Trade Names*, Industrial Research Service, Dover, N. H., 1953.

SPECIFIC REFERENCES

"*Sec.*" refers to the section of number shown in 35 U.S. Code, the Trade-Mark Act of 1946, Public Law 489, 79th Congress, 60 Statutes 427; "*Rule*" to the Patent Office Rules in Trade-Mark Cases; "*U.S.*" to Supreme Court Decisions in U.S. Reports, the volume being the first number shown; and "*P.Q.*" to United States Patents Quarterly.

(1) Pastificio Spiga *v.* DeMartini Macaroni, *P.Q.*, **95**, 305.
(2) Mishawaka Rubber *v.* Kresge, *U.S.*, **316**, 203.
(3) *National Family Opinion Survey*, Brand Names Foundation, N.Y., 1950.
(4) Delta Laboratories *v.* Copper Tan, *P.Q.*, **100**, 237.
(5) Schechter, F. I., *Historical Foundations of the Law Relating to Trade-Marks*, Columbia Univ. Press, 1925; J. H. Merchant, *J. Patent Office Soc.*, **36**, 341 (1954).
(6) Derenberg, W. J., *Sixth Year of Administration of the Lanham Trade-Mark Act*, Bureau of National Affairs, Washington, 1953; *Trade-Mark Reptr.*, **43**, 779.
(7) Ex parte Jacobson, *P.Q.*, **97**, 465.
(8) Greenberg, A. S., *J. Patent Office Soc.*, **32**, 745.
(9) Bama *v.* Goltsman, *P.Q.*, **88**, 1.
(10) Kellogg *v.* National Biscuit, *U.S.*, **305**, 111.
(11) Standard Brands Inc. *v.* Smidler, *P.Q.*, **62**, 135.
(12) Ford Motor *v.* Ford Insecticide, *P.Q.*, **72**, 355.
(13) United Drug *v.* Ar-Ex Cosmetics, *P.Q.*, **70**, 362.
(14) Ex parte Lustur-Seal, *P.Q.*, **96**, 247.
(15) Bunte *v.* Shedd Products, *P.Q.*, **91**, 14.
(16) *Sec. 2.*
(17) *Sec. 23.*
(18) Rossman, J., *Chem. Eng. News*, **24**, 3640 (1948).
(19) *Sec. 45, cf. Sec. 23.*
(20) Ex parte The Standard Oil Co., *P.Q.*, **92**, 259.
(21) *Rule 7.9.*
(22) *Rule 16.1.*
(23) *Sec. 31.*
(24) *Sec. 1 (a), 2 (d), 17, 18.*
(25) *Sec. 29.*
(26) In re Eastman Kodak, *P.Q.*, **27**, 343.
(27) Pro-Phy-Lactic Brush *v.* Lawson, *P.Q.*, **32**, 262.
(28) General Engineering & Mfg. *v.* Gemmill, *P.Q.*, **72**, 234.
(29) *Sec. 43 (a).*
(30) Ex parte Globe Wernicke, *P.Q.*, **96**, 189.
(31) *Sec. 14.*
(32) Du Pont Cellophane *v.* Waxed Products, *P.Q.*, **30**, 332
(33) *Sec. 45.*
(34) Arrow Importing *v.* Driesen, *P.Q.*, **74**, 66.

(35) Prichard *v.* Consumers Brewing, *P.Q.*, **58**, 362.
(36) Du Pont *v.* American Cellulose, *P.Q.*, **69**, 258; *P.Q.*, **77**, 364.
(37) *Sec. 14, 24.*
(38) Champion Spark Plug *v.* Perfect Recondition Spark Plug, *P.Q.*, **73**, 133.
(39) Prestonettes *v.* Coty, *U.S.*, **264**, 359.
(40) *Sec. 32 (1).*
(41) *Sec. 33 (a).*
(42) McLean *v.* Fleming, *U.S.*, **96**, 245.
(43) Best *v.* Miller, *P.Q.*, **77**, 133.
(44) *Sec. 44 (c).*
(45) *Sec. 35.*
(46) Langner, Parry, Card, and Langner, *Bull.* (1954).
(47) Robinson, Arnold, private communication.

ROBERT CALVERT

TRAGACANTH. See *Gums and mucilages*, Vol. **7**, p. 333.

TRANSAMINASES. See *Enzymes*, Vol. **5**, p. 744.

TRANSFORMER OILS. See *Dielectrics*, Vol. **5**, p. 63; *Petroleum (products)*, Vol. **10**, p. 174.

TRANSISTOR MATERIALS. See *Germanium*, Vol. **7**, p. 169; *Silicon and silicon alloys*, Vol. **12**, p. 364.

TRANSMITTANCE, TRANSMITTANCY. See *Colorimetry and fluorimetry*, Vol. **4**, p. 268.

TRANSMITTANCY CURVES. See *Dyes (evaluation)*, Vol. **5**, p. 438.

TRANSPORT NUMBERS. See "Transference numbers" under *Electrochemistry*, Vol. **5**, p. 533.

TRAVELING-WAVE TUBES. See *Electronics*, Vol. **5**, p. 560.

α,α-TREHALOSE, $CH_2OHCHO(CHOH)_3CHOCH(CHOH)_3CHOCH_2OH$. See *Sugars (survey)*, Vol. **13**, pp. 234, 236.

TREMOLITE, $Ca_2Mg_5Si_8O_{22}(OH)_2$. See *Asbestos*, Vol. **2**, pp. 135, 136; *Silica and silicates (mineral)*, Vol. **12**, p. 279.

TRIACETIN, $C_3H_5(OOCCH_3)_3$. See *Glycerol*, Vol. **7**, p. 227.

TRIARYLMETHANE DYES. See *Triphenylmethane and diphenylnaphthylmethane dyes.*

1,3,5-TRIAZINES, *s*-TRIAZINES, $N:CX.N:CX.N:CX$. See *Heterocyclic compounds*, Vol. **7**, p. 453.

TRIAZOLES, $C_2H_3N_3$. See *Heterocyclic compounds*, Vol. **7**, p. 444.

TRIBROMOETHANOL, CBr_3CH_2OH. See *Anesthetics*, Vol. **1**, p. 907; *Bromine compounds (organic)*, Vol. **2**, p. 658.

TRI-*n*-BUTYL PHOSPHATE, $(C_4H_9)_3PO_4$. See *Plasticizers*, Vol. **10**, p. 780.

TRICHLOROACETIC ACID, CCl_3COOH. See *Acetic acid*, Vol. **1**, p. 77.

TRICHLOROETHYLENE, $CHCl:CCl_2$. See *Anesthetics*, Vol. **1**, p. 906; *Chlorine compounds, organic*, Vol. **3**, pp. 733, 788.

TRICHLOROSILANE, $SiHCl_3$. See *Silicon compounds (inorganic)*, Vol. **12**, p. 368; *Silicones*, Vol. **12**, p. 395.

TRICHOMYCIN. See *Streptomyces antibiotics (survey)*, Vol. **13**, p. 61.

TRICOSANOIC ACID, *n*-TRICOSOIC ACID, $CH_3(CH_2)_{21}COOH$. See *Fatty acids*, Vol. **6**, pp. 174, 257.

TRICRESYL PHOSPHATE, $(CH_3C_6H_4)_3PO_4$. See *Plasticizers*, Vol. **10**, p. 782.

TRIDECANOIC ACID, *n*-TRIDECYLIC ACID, $CH_3(CH_2)_{11}COOH$. See *Fatty acids*, Vol. **6**, pp. 174, 252.

TRIDYMITE, SiO_2. See *Silica*, Vol. **12**, p. 273.

TRIGONELLINE, $C_7H_7NO_2$. See *Alkaloids*, Vol. **1**, p. 476.

TRIHEXYPHENIDYL, $HOC(C_6H_5)(C_6H_{11})CH_2CH_2NC_5H_{10}$. See *Stimulants and depressants*, Vol. **13**, p. 17.

TRILUPINE, $C_{15}H_{24}N_2O_3$. See *Alkaloids*, Vol. **1**, p. 482.

TRIMETHADIONE, $CH_3N.CO.C(CH_3)_2.O.CO$. See *Hypnotics and sedatives*, Vol. **7**, p. 776; *Stimulants and depressants*, Vol. **13**, p. 15.

2,6,8-TRIMETHYL-4-NONANONE, $(CH_3)_2CHCH_2COCH_2CH(CH_3)CH_2CH(CH_3)_2$. See *Ketones*, Vol. 8, p. 133.

TRIMETHYLOLPROPANE, $CH_3CH_2C(CH_2OH)_3$. See *Butyraldehyde*, Vol. **2**, p. 691.

1,3,5-TRINITROBENZENE, $C_6H_3(NO_2)_3$. See *Explosives (high)*, Vol. **6**, p. 42.

2,4,6-TRINITROTOLUENE, $CH_3C_6H_2(NO_2)_3$. See *Explosives (high)*, Vol. **6**, p. 43.

***s*-TRIOXANE, α-TRIOXYMETHYLENE.** See *Formaldehyde*, Vol. **6**, pp. 862, 863, 869.

TRIPELENNAMINE HYDROCHLORIDE. See *Histamine and antihistamine agents*, Vol. **7**, p. 472; *Pyridine*, Vol. **11**, p. 292.

TRIPHENYLMETHANE, $(C_6H_5)_3CH$. See *Hydrocarbons*, Vol. **7**, pp. 613, 645.

TRIPHENYLMETHANE AND DIPHENYLNAPHTHYLMETHANE DYES

The triarylmethane dyes are derivatives of triphenylmethane, $(C_6H_5)_3CH$, and of diphenylnaphthylmethane, $(C_6H_5)_2CHC_{10}H_7$, to which auxochromic and bathochromic groups have been added (see Vol. **2**, p. 230). Broadly speaking, the phthaleins and the 9-phenylacridines fall in this category since in their preparation triphenylmethane derivatives are formed as precursors. However, these classes of dyes are discussed more appropriately under *Xanthene dyes* (*q.v.*) and *Acridine dyes* (see Vol. **1**, p. 170). See also *Phenolphthalein*, Vol. **10**, p. 371; "Sulfonephthaleins," Vol. **13**, p. 439.

Vivid shades of red, violet, blue, and green are to be found among the triarylmethane dyes. Such brilliancy of hues can only be duplicated at far greater expense by other dyes (for example, the wool dyes of the anthraquinone series).

The triarylmethane dyes were among the first synthetic dyes to attract the attention of dyers and chemists. Perkin's discovery in 1856 of the dye mauve (mauveine) with its subsequent financial rewards encouraged other workers to exploit the field of synthetic dyes, and soon afterward (1859) Verguin prepared the first dye of the triphenylmethane series by heating crude aniline with stannic chloride. (Actually, Nathanson and Hofmann had independently prepared the same dye a little earlier but had failed to realize its technical importance.) Verguin's red dye was patented by the French firm of Renard Frères and Franc, in 1859, and introduced to the world under the name Fuchsine, derived apparently from "Fuchs" (fox, the equivalent of

the firm's name Renard in German) or from "fuchsia" because of the color resemblance to the red flower of the plant of this name. The dye was also called Magenta in commemoration of the victory of the French over the Italians at Magenta in 1859. The name Rosaniline was given to it by Hofmann on account of its source, aniline, and its rose-red color. At one time this dye sold for as much as one hundred dollars per pound.

Dyes of this class are notoriously poor in fastness properties and, in spite of intensive research to improve their properties, only a relatively few triphenylmethane dyes come up to the azo dyes in fastness. From the standpoint of the dyer, the triarylmethane dyes may be classified as acid, basic, mordant acid, and direct (see Vol. 4, pp. 368, 372, 378, 381).

Although they have lost a great deal of their former importance, they still are produced in fairly large quantities (see Table I, giving U.S. Tariff Commission figures), primarily because of their brilliancy coupled with cheapness and their specialized uses.

TABLE I. U.S. Production and Sales of Triphenylmethane and Diphenylnaphthylmethane Dyes, 1953.

C.I. no.	Dye	Production, lb.	Sales	
			Quantity, lb.	Value, $
657	Malachite Green	378,000	369,000	689,000
658	Setoglaucine	—	19,000	54,000
662	Brilliant Green	116,000	97,000	235,000
666	Guinea Green B	155,000	156,000	135,000
667	Brilliant Milling Green B	30,000	20,000	73,000
671	Erioglaucine	664,000	462,000	527,000
676	Para Magenta (Parafuchsine)	10,000	6,000	19,000
680	Methyl Violet B and base	1,453,000	1,112,000	1,127,000
681	Crystal Violet	825,000	791,000	1,525,000
682	Ethyl Violet	—	17,000	46,000
698	Formyl Violet S4B	139,000	116,000	182,000
707[a]	Soluble Blue	114,000	88,000	257,000
720	Eriochrome Azurol B	102,000	118,000	252,000
722	Eriochrome Cyanine R	—	22,000	62,000
729	Victoria Blue B	143,000	139,000	315,000
735	Naphtalin Green V	—	63,000	151,000
737	Wool Green S	133,000	106,000	108,000
Pr. no.				
198	Victoria Pure Blue B	167,000	129,000	423,000
223	Brilliant Indocyanine	—	7,000	37,000

[a] See p. 318.

Triphenylmethane and diphenylnaphthylmethane dyes find use in the dyeing of silk, mordanted cotton, and paper. Large quantities of certain types find extensive use in the field of copying papers and in the manufacture of lakes (see Vol. **10**, p. 679). In addition, they are used in writing and printing inks (see Vol. **7**, p. 872; Vol. **11**, p. 152), as food, drug, and cosmetic colors (see Vol. **4**, p. 287), and as microbiological stains (see Vol. **12**, p. 743).

Of recent years, considerable interest has developed in moth inhibitors of the triphenylmethane series and some "colorless dyes" for use in mothproofing are now on the market.

CONSTITUTION

Although Fuchsine (Parafuchsine—see p. 316) was discovered before 1860, it took about twenty years before its structure was definitely established. This proof laid the foundation for the structure of other triphenylmethane dyes.

Hofmann was the first to show that parafuchsine possessed the formula $C_{19}H_{19}N_3$. On the basis of other pieces of evidence, Otto and E. Fischer finally in the last quarter of the 19th century firmly established the structure of Parafuchsine as a triamino-triphenylmethane.

They showed that the unoxidized Parafuchsine derivative known as the leuco base contained three primary amino groups which were removed by diazotization and boiling with alcohol. This gave triphenylmethane, which was known at that time:

$$C_{19}H_{13}(NH_2)_3 \longrightarrow C_{19}H_{13}(N_2Cl)_3 \longrightarrow HC(C_6H_5)_3$$

They then reversed the process by nitrating triphenylmethane, reducing to the amine (leuco base), oxidizing to the carbinol base, and forming the acid salt of the dye:

$$HC(C_6H_5)_3 \longrightarrow HC(C_6H_4NO_2)_3 \longrightarrow HC(C_6H_4NH_2)_3 \longrightarrow HOC(C_6H_4NH_2)_3 \longrightarrow$$

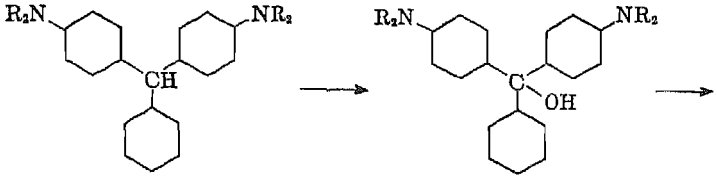
$$C(C_6H_4NH_2)_2(C_6H_4{=}NH_2Cl)$$

This dye was identical with Parafuchsine.

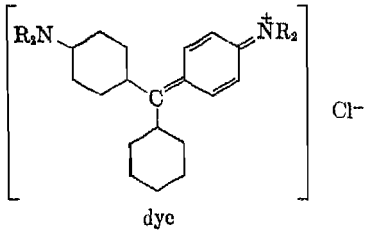
The positions of the three amino groups were established as para, as follows: Aniline and benzaldehyde were condensed to give a diaminotriphenylmethane, which by diazotization and decomposition gave *p,p'*-dihydroxybenzophenone. If, instead of benzaldehyde, *p*-nitrobenzaldehyde was condensed with aniline, a nitrodiaminotriphenylmethane was produced, which, on reduction, gave leuco Parafuchsine.

Although the structures of the leuco and carbinol bases have been established beyond a doubt, the question as to the color and constitution of the dyes themselves has not yet been settled to everyone's satisfaction. Only a brief discussion will be given here; for further details, particularly of the not so recent work, the reader is referred to the publications of Hantzsch and Ostwald, Wizinger (23), Kehrmann (13), v. Baeyer, Pfeiffer, and Ramart-Lucas (19).

SCHEME 1



leuco base (colorless) carbinol base (colorless)



dye

The formation of a triphenylmethane dye can be conceived of as going through the following stages: formation of the colorless leuco base, conversion of this to the colorless carbinol or color base, and finally formation of the dye by treatment with acid (see Scheme 1). The quinoneimine formulation of the cation shown was proposed many years ago. However, this structure cannot explain the intense color of these dyes in solution. Other formulations, of which there have been many, have also failed to satisfactorily explain all the facts. The best formulation most generally accepted today is the representation of the dye molecule as a resonance hybrid (see Vol. **2**, p. 231; Vol. **4**, p. 254).

CLASSIFICATION

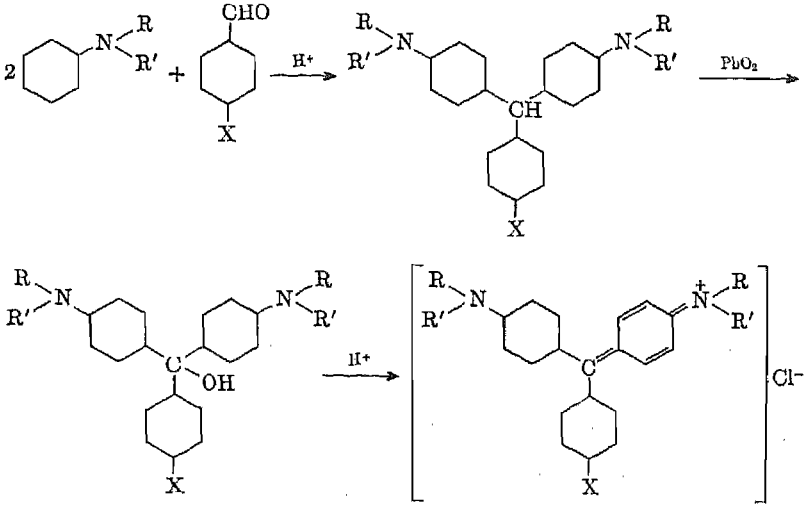
An alternate or additional classification of the triarylmethane dyes to the division into the triphenylmethanes and the diphenylnaphthylmethanes is one based on substitution in the aromatic nuclei: (*1*) the diaminotriarylmethanes or dyes of the Malachite Green series; (*2*) the triaminotriarylmethanes or dyes of the Fuchsine (Rosaniline or Magenta) series; and (*3*) the hydroxytriarylmethanes or dyes of the Rosolic Acid series. A fourth grouping of amino hydroxy derivatives is sometimes made (see Vol. **5**, p. 348). Monoaminotriarylmethanes are known but they are not included in the classification since they have few or no dyeing characteristics.

PREPARATION

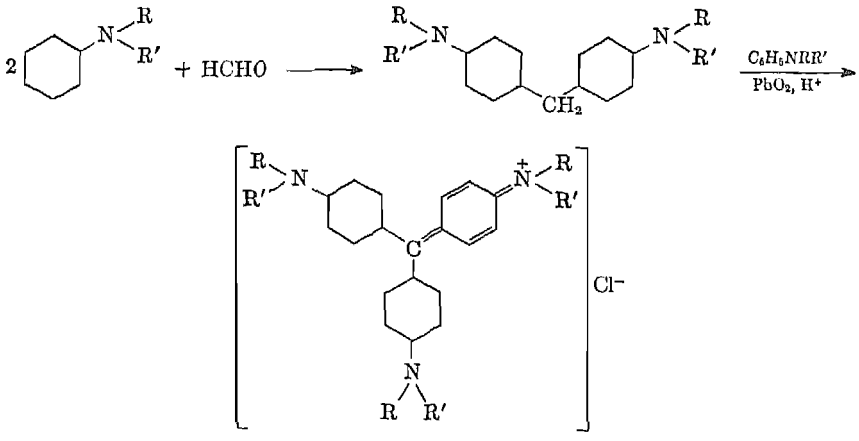
Many methods have been described for the preparation of triphenylmethane dyes but actually only a few have achieved industrial importance. The major difference in the methods that are used industrially lies in the source of the central carbon atom.

(*1*) The central carbon atom is furnished by an aromatic aldehyde, or a substance capable of giving rise to an aldehyde during the course of the condensation. The aldehyde is condensed with a tertiary aminobenzene in which the substituents on the nitrogen atom may be alike or different. The resulting leuco compound is then oxidized to the carbinol base, which in the presence of acid is converted to the dye (see

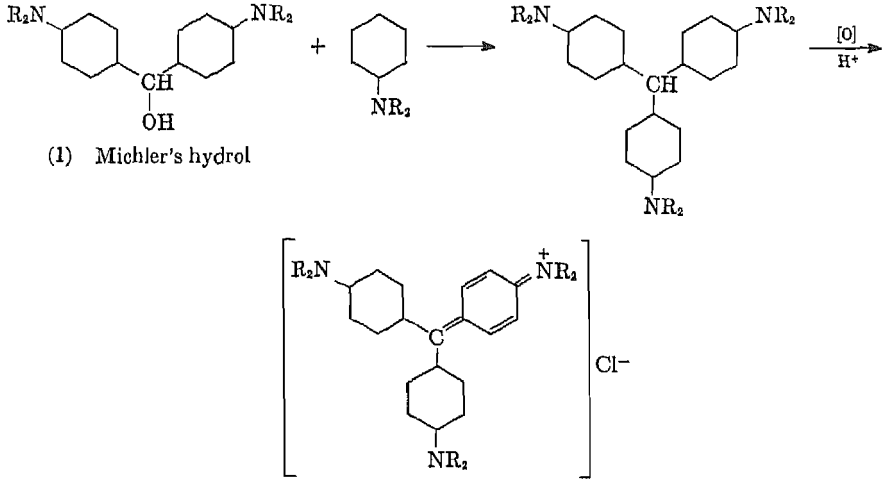
SCHEME 2



SCHEME 3

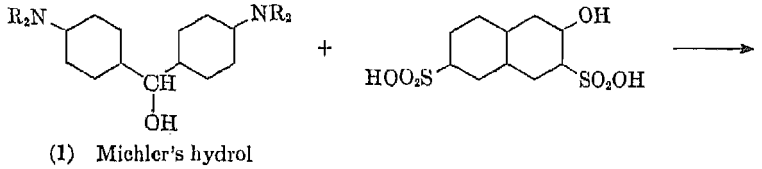


SCHEME 4



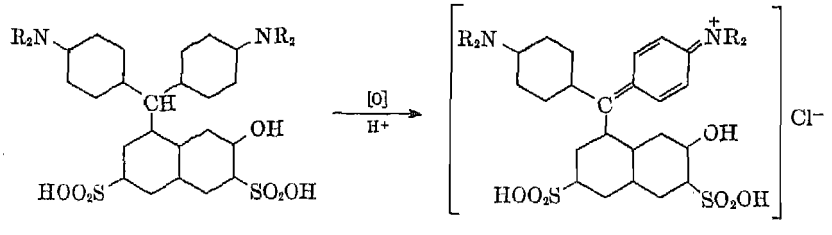
(1) Michler's hydrol

(1)



(1) Michler's hydrol

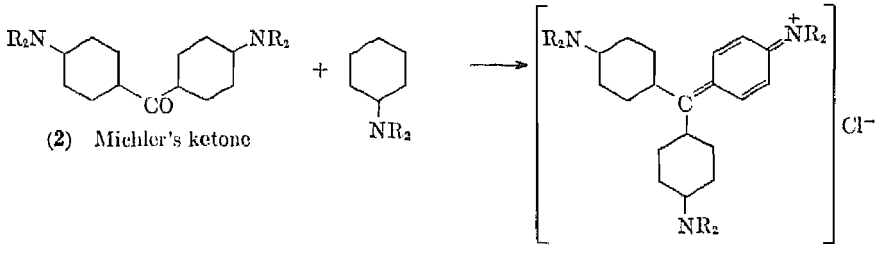
(2)



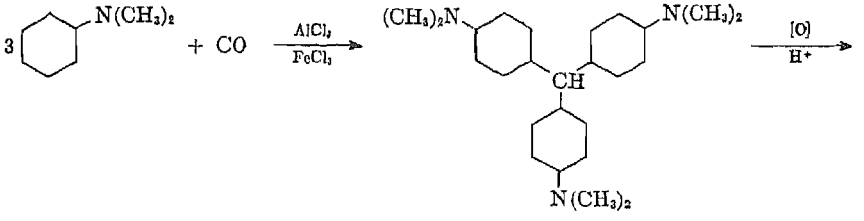
Scheme 2 (where X = any group, R = R′, or R and R′ are different with R or R′ = H, alkyl, aralkyl, alkanol, etc.).

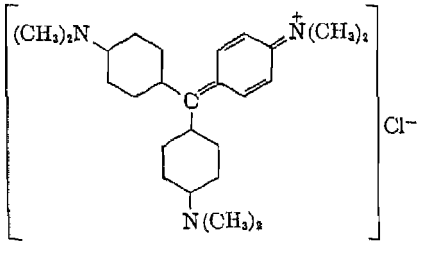
(*2*) The central carbon atom is furnished by the condensate from formaldehyde

SCHEME 5



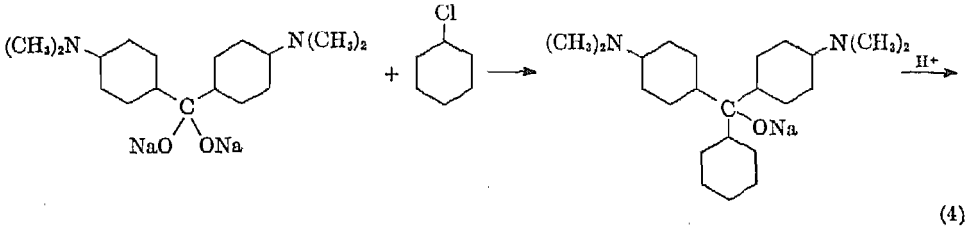
SCHEME 6



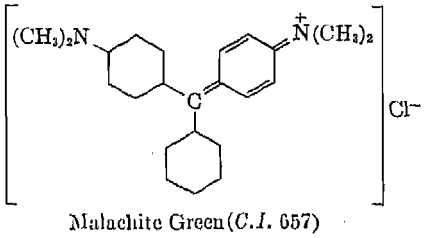


(3)

Crystal Violet (*C.I.* 681)



(4)



Malachite Green (*C.I.* 657)

and a tertiary arylamine, which on oxidation with the same or a different tertiary aminobenzene, in the presence of acid, gives rise to the dye (see Scheme 3).

(*3*) The central carbon atom is furnished by the so-called Michler's hydrol (**1**) (see Scheme 4, where R is usually methyl or ethyl but may be different). This method is of special importance since this hydrol condenses fairly easily not only with various primary, secondary, and tertiary arylamines (eq. (*1*)) but also with the sulfo and hydroxy derivatives of naphthalene (eq. (2)). (The condensation will also take place with the nonhydroxylated 2,7-disulfonic acid.) The resulting leuco dye, on oxidation in the presence of acid, is converted to the dye.

(*4*) The central carbon atom is furnished by a diaryl ketone, Michler's ketone (**2**), which is condensed directly with a tertiary arylamine having a free para position (see Scheme 5).

Two other methods (eq. (3) (ref. 15) and eq. (4)) are shown in Scheme 6, not because they are of practical importance at present, but merely to illustrate further the many diversified methods that have been proposed for the synthesis of triphenylmethane dyes.

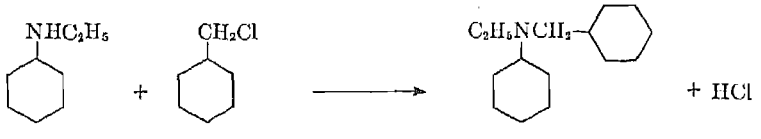
Actually some of these methods are interrelated. For instance, method (*1*) no doubt goes through method (*3*), and it is conceivable that method (*2*) may proceed through method (*3*).

Where it is necessary to oxidize a leuco compound, the following oxidants are used commercially: lead dioxide, sodium dichromate, manganese dioxide, and nitrosylsulfuric acid. In general, if the oxidation is improperly carried out, the resulting dye will have a dull appearance.

Intermediates

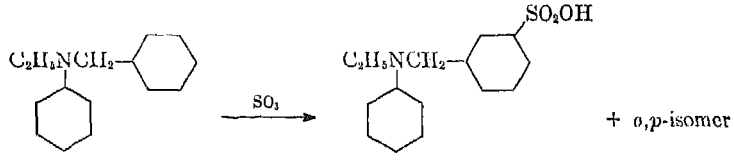
Many of the intermediates used in the manufacture of triarylmethanes are well known (see Vol. **5**, p. 343). Several, however, are not commonly encountered in other fields of dye chemistry.

One of the most important tertiary **amines** used in the manufacture of triphenylmethane dyes is *ethylbenzylaniline* (see Vol. **1**, p. 924). This is commonly prepared by the reaction of monoethylaniline with benzyl chloride followed by fractionation of the condensate over caustic soda (ref. 10, p. 135):



Other tertiary amines, such as methylbenzylaniline and *N*-ethyl-*m*-toluidine, can be similarly prepared.

On sulfonation of ethylbenzylaniline, a sulfonic acid group is introduced chiefly into the meta position and not, as was formerly believed, into the para position (3). See "*α*-(*N*-Ethylanilino)toluene-*m*-sulfonic acid" under *Toluenesulfonic acids*.



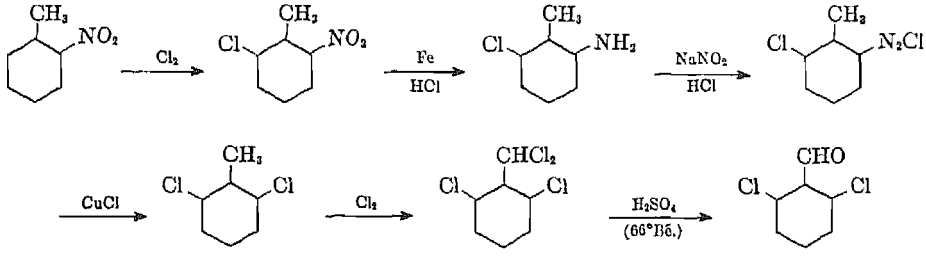
N-Ethyl-1-naphthylamine, $C_{10}H_7NHC_2H_5$, b.p. 305°C., is prepared in about 75% yields from naphthylamine and ethyl chloride under pressure. *N-Phenyl-1-naphthylamine*, $C_{10}H_7NHC_6H_5$, m.p. 62°C., is readily obtained by the reaction of 1-naphthylamine and aniline in the presence of sulfanilic acid or *p*-toluenesulfonic acid (ref. 10, p. 179).

Of the **aldehydes,** three deserve mention. *Benzaldehyde-o-sulfonic acid* (*o*-formylbenzenesulfonic acid, *o*-sulfobenzaldehyde), $HO_2SC_6H_4CHO$, is made on a large scale by the replacement of the chloro group in *o*-chlorobenzaldehyde with the $-SO_2OH$ group by heating with sodium sulfite under pressure (ref. 8, Vol. **1**, p. 57). In 1953, the U.S. production was 125,000 lb.

Benzaldehyde-2,4-disulfonic acid (4-formyl-*m*-benzenedisulfonic acid), $(HOSO_2)_2C_6H_3CHO$, is made by the oxidation of toluene-2,4-disulfonic acid with potassium permanganate in the presence of manganous sulfate and sulfuric acid.

2,6-Dichlorobenzaldehyde, m.p. 70–71°C., is one of the few examples illustrating the use of the Sandmeyer reaction on a large scale in the dye field. The steps in the preparation, starting with *o*-nitrotoluene, are shown in Scheme 7 (ref. 10, p. 160).

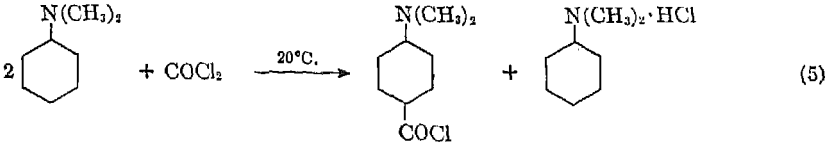
SCHEME 7



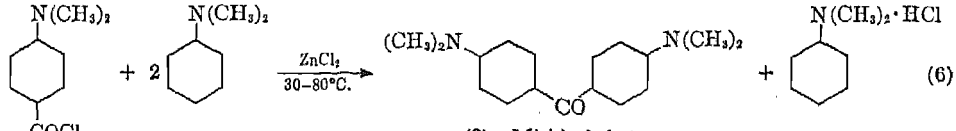
Two other intermediates that are used practically only in the preparation of triphenylmethanes are Michler's ketone and its reduction product, Michler's hydrol. In 1953, the U.S. production of Michler's ketone was 141,000 lb., and of Michler's hydrol, 11,000 lb.

Michler's ketone (tetramethyl-*p,p'*-diaminobenzophenone, 4,4'-bis(dimethylamino)benzophenone) **(2)** crystallizes from alcohol in colorless leaflets, m.p. 173–74°C. It is insoluble in water, moderately soluble in alcohol, and readily soluble in warm benzene. Alkaline reduction of Michler's ketone gives the corresponding carbinol,

SCHEME 8



(5)



(6)

(2) Michler's ketone

Michler's hydrol, and more drastic reduction leads to *p,p'*-tetramethyldiaminodiphenylmethane.

This ketone was first prepared by Michler in 1900. He found that if phosgene is passed into dimethylaniline at room temperature until the increase in weight corresponds with the proportion of one mole of phosgene to two moles of dimethylaniline, *p*-(dimethylamino)benzoyl chloride is formed (Scheme 8, eq. (5)). By a modified Friedel-Crafts reaction (see Vol. **6**, p. 890) in the presence of excess dimethylaniline at a higher temperature, the acid chloride is converted to Michler's ketone (eq. (6)). About 75–80% of the theoretical yield of Michler's ketone is obtained along with the *o,o'*- and *o,p'*-isomers.

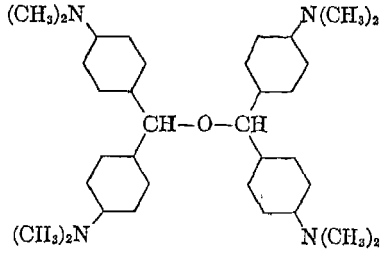
Another method (which is not in use) for the preparation of Michler's ketone in 96% yields involves the action of dimethylamine on 4,4'-dichlorobenzophenone in the presence of copper salts under pressure (9,30). This method is not economically feasible because of the high cost of the benzophenone derivative.

The main use of Michler's ketone is in the manufacture of Crystal Violet (*C.I.* 681) and the Victoria Blues (*C.I.* 690, 728, 729). For the manufacture of certain dyes, Michler's ketone is not isolated but is further condensed to give the desired products (see p. 320).

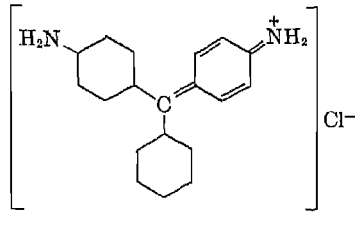
The ketonimine dye Auramine (Auramine O) (*C.I.* 655) (see Vol. 8, p. 152) was originally prepared from this ketone by heating it with ammonium chloride and anhydrous zinc chloride at 150–60°C.

Tetraethyl-*p,p'*-diaminobenzophenone is prepared similarly to Michler's ketone from diethylaniline instead of dimethylaniline.

Michler's hydrol (tetramethyl-*p,p'*-diaminobenzhydrol) **(1)** forms colorless needles, m.p. 101–3°C., on recrystallization from hot alcohol, benzene, or ether. On heating above its melting point, it forms the dihydryl ether **(3)**, which is the chief impurity in the technical product (ref. 10, p. 139). With glacial acetic acid, it gives a deep blue color. The hydroxyl group is extremely reactive, being readily alkylated by mere warming with alcohols. It is this great reactivity that gives this intermediate its importance.



(3) Dihydryl ether from Michler's hydrol

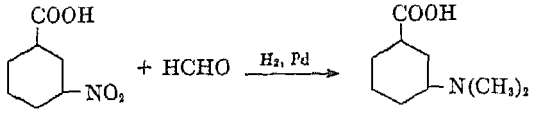


(4) Doebner's Violet

Although Michler's hydrol can be obtained by alkaline reduction of Michler's ketone, it is produced industrially by the oxidation of *p,p'*-tetramethyldiaminodiphenylmethane (4,4'-methylenebis(*N,N*-dimethylaniline), methane base) by lead dioxide or manganese dioxide. Methane base, m.p. 91–92°C., is prepared, in turn, from dimethylaniline and formaldehyde according to the first step of the reaction in Scheme 3 (p. 306) (see also Scheme 13, p. 320).

Both Michler's hydrol and its ethyl analog are used in the manufacture of dyes of the Naphthalene Green series and certain alkylated Fuchsines.

***m*-Dimethylaminobenzoic acid** can be prepared in almost theoretical yield by the reductive alkylation of an alcoholic solution of *m*-nitrobenzoic acid and aqueous formaldehyde using palladized charcoal as a catalyst, in an atmosphere of hydrogen at room temperature and pressure (4). The overall equation may be written:



It is used in preparing Crystal Violet lactone.

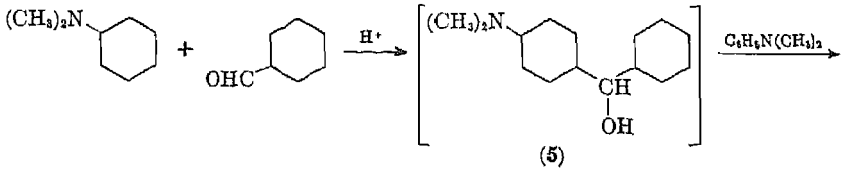
Diaminotriarylmethane Dyes (Malachite Series)

Although many dyes of this series have been described, relatively few have achieved technical significance. The prototype of the series, Doebner's Violet (4), is without practical importance. It is only after substitution of the amino hydrogens by alkyl and/or aralkyl groups that valuable green dyes are obtained.

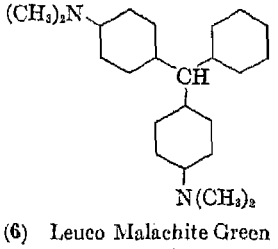
Malachite Green (7) (*C.I.* 657), the first important member of this series, was discovered by O. Fischer in 1877. It is the completely methylated derivative of Doebner's Violet and is manufactured on a large scale by acid condensation of benzaldehyde with an excess of dimethylaniline. The name "Malachite Green" was given to this dye because of its resemblance to the beautiful green copper mineral malachite. Because benzaldehyde is used in its manufacture, it is also known as Benzaldehyde Green.

The method of preparation is typical for many dyes of this series. Benzaldehyde and a slight excess of dimethylaniline are heated at 100°C. for 24 hours using hydrochloric or sulfuric acid as the condensing agent. The amount of condensing agent used is important, about two-thirds of a mole of acid giving the best results. According to Fierz-David (ref. 9, p. 227), an excess of acid leads to the formation of *p*-dimethylaminobenzhydrol which is incapable of taking part in the dye formation. On the other hand, recent work has indicated that the formation of Malachite Green goes through the benzhydrol stage (5) to the leuco base (6) (5,21). See Scheme 9.

SCHEME 9



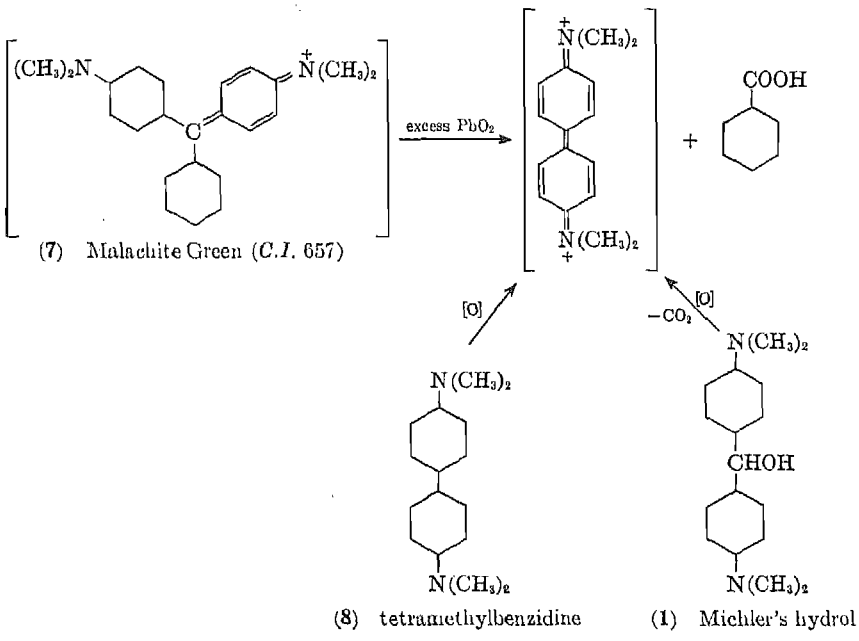
(5)



(6) Leuco Malachite Green

After condensation has been completed, the reaction mass is made alkaline and the excess dimethylaniline removed by steam distillation. The resulting leuco compound is dissolved in hydrochloric acid and the diluted solution oxidized cold with freshly prepared lead dioxide. It is extremely important that the amount of oxidant used be calculated very carefully if over-oxidation is to be avoided. Kehrmann (14) has shown that in the case of Malachite Green, over-oxidation leads to the formation of a quinone imine identical with that formed by oxidizing tetramethylbenzidine (8) or Michler's hydrol (1) (see Scheme 10).

SCHEME 10



(7) Malachite Green (*C.I.* 657)

(8) tetramethylbenzidine

(1) Michler's hydrol

After the oxidation of the leuco base, the lead chloride is precipitated by the addition of sodium sulfate, and the dye solution is filtered from the lead sulfate and subsequently separated by making alkaline. The carbinol so formed, upon adding to a solution of oxalic acid, is then converted to the beautifully crystalline oxalate of the dye. More rarely, Malachite Green is isolated as the zinc chloride double salt.

Malachite Green finds extensive use in the paper trade and in the manufacture of ink toners (see Vol. **10**, p. 675). Very little is used for dyeing cotton.

Brilliant Green (*C.I.* 662) is the diethyl analog of Malachite Green and gives somewhat yellower shades. It usually appears on the market as the sulfate. Its method of preparation follows that of Malachite Green.

ACID GREENS

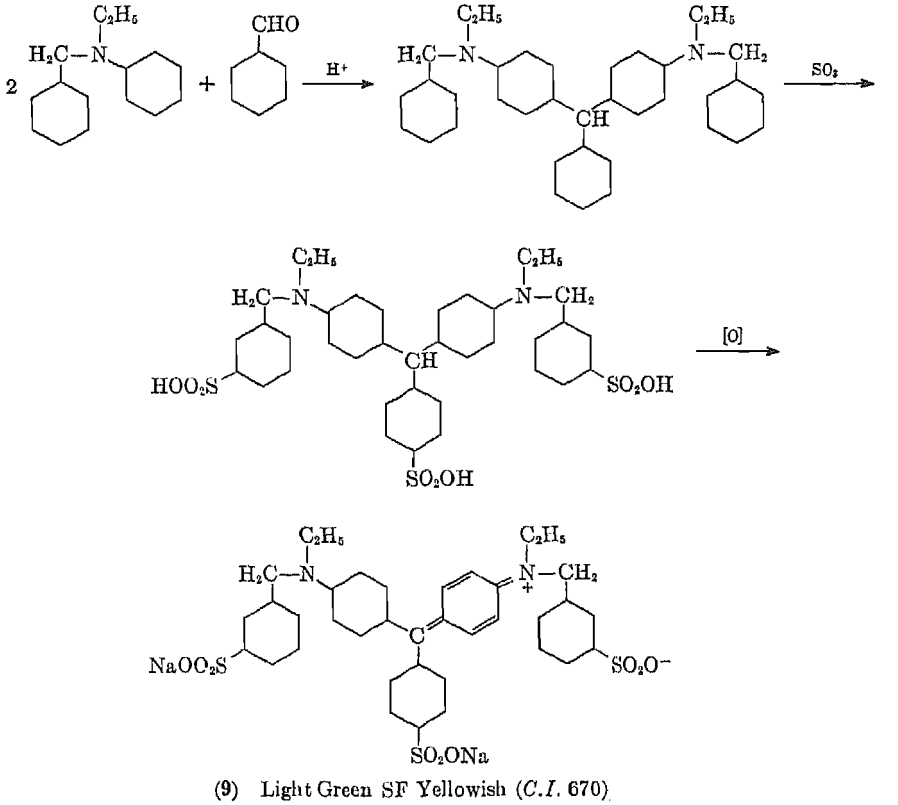
Helvetia Green (*C.I.* 660) is the *p*-monosulfonic acid of Malachite Green made by the direct sulfonation of Malachite Green or its leuco derivative (32). It was the first member of the so-called Acid Greens useful for the dyeing of wool and silk, but it has long vanished from dye markets because of its extreme alkali sensitivity. Acid

Greens as a class are no better in alkali- or lightfastness than their unsulfonated predecessors.

In general, one sulfonic acid group does not confer sufficient solubility on a dye of the Malachite series and it is customary to introduce two or more such groups in order to obtain technically usable products. To this end, two different methods are used, both on a fairly large scale: (*1*) either an *N*-alkylbenzylaniline, $C_6H_5N(R)CH_2C_6H_5$, is used in forming the leuco compound, which can then be readily sulfonated, or (*2*) a suitable sulfonic acid derivative is used in the formation of the desired leuco derivative.

For example, **Light Green SF Yellowish** (FD&C Green No. 2, D&C Green No. 4) **(9)** (*C.I.* 670) is prepared by condensing benzaldehyde with ethylbenzylaniline, sulfonating the leuco derivative to a trisulfo compound, and subsequently oxidizing to the dye (see Scheme 11; the meta sulfo groups are shown as para in the *Colour Index*). Light Green SF Yellowish has very poor lightfastness but does find use for coloring food.

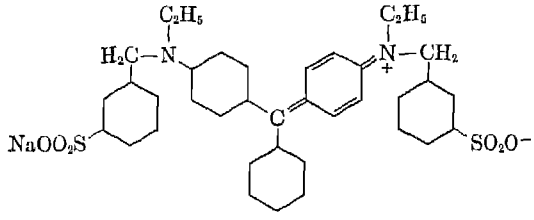
SCHEME 11



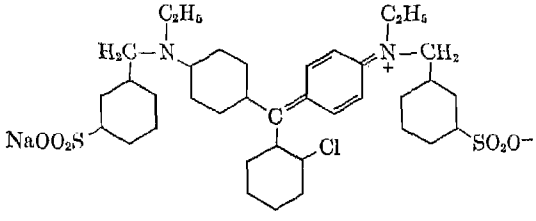
(9) Light Green SF Yellowish (*C.I.* 670)

Guinea Green B (FD&C Green No. 1, Acid Green B) **(10)** (*C.I.* 666) is prepared by condensing benzaldehyde with ethylbenzylanilinesulfonic acid (α-(*N*-ethylanilino)-*m*-toluenesulfonic acid) and oxidizing the resulting leuco compound to the dye.

Similarly, **Brilliant Milling Green B** (D&C Green No. 7, Fast Acid Green B) **(11)** (*C.I.* 667) is made by starting with *o*-chlorobenzaldehyde and ethylbenzylaniline-sulfonic acid.



(10) Guinea Green B (*C.I.* 666)

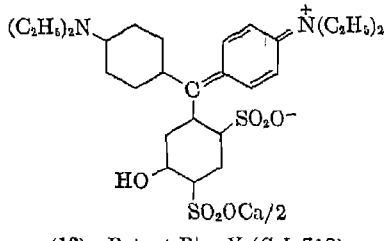


(11) Brilliant Milling Green B (*C.I.* 667)

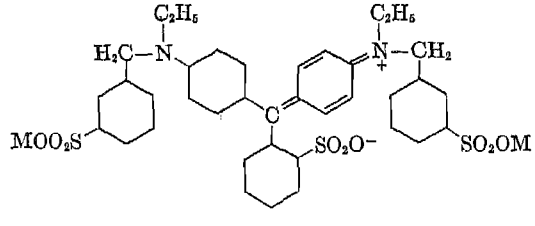
Other sulfonated intermediates used for introducing sulfonic acid groups into the dye molecule are benzaldehyde-*o*-sulfonic acid, benzaldehyde-2,4-disulfonic acid, and naphthalene-2,7-disulfonic acid (see Vol. **9,** p. 239). These intermediates confer unexpected properties such as alkali-fastness upon the Acid Greens.

PATENT BLUES

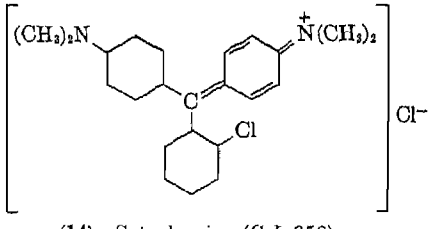
In 1888, Herrmann prepared an acid dye, **Patent Blue V (12)** (*C.I.* 712), which had improved alkali- and lightfastness. This dye was prepared by condensing *m*-hydroxybenzaldehyde with two moles of diethylaniline, sulfonating the leuco base, and oxidizing to the dye. Patent Blue V was the first member of a small but important group of acid dyes known as the Patent Blues. **Patent Blue A** (D&C Blue No. 8) (*C.I.* 714) is the corresponding dye from *m*-hydroxybenzaldehyde and ethylbenzyl-



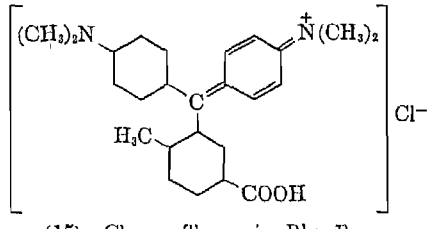
(12) Patent Blue V (*C.I.* 712)



(13) Erioglaucine (*C.I.* 671)



(14) Setoglaucine (*C.I.* 658)



(15) Chrome Turquoise Blue B

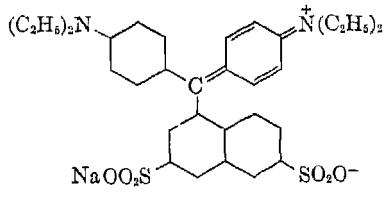
aniline. The simplest member of the Patent Blues is **Xylene Blue** VS (*C.I.* 672) made from benzaldehyde-2,4-disulfonic acid and diethylaniline (2).

Erioglaucine (**13**; M = NH_4 or Na) (*C.I.* 671) (D&C Blue No. 4, Acid Glaucine Blue, the diammonium salt; FD&C Blue No. 1, corresponding disodium salt) is the dye resulting from the condensation of two moles of ethylbenzylanilinesulfonic acid with one mole of benzaldehyde-*o*-sulfonic acid (2) (the two meta sulfo groups are represented as para in the *Colour Index*). It finds extensive use in the manufacture of the beautiful blue toner *Peacock Blue* (see Vol. **10,** pp. 679–81).

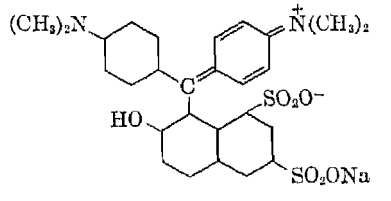
The importance of the Patent Blues lies not only in their increased alkali- and light-fastness but also in their increased level-dyeing character. At first it was believed that the property of increased alkali-fastness was due to the hydroxyl group meta to the central carbon atom; later, however, Sandmeyer showed that it was the sulfonic acid group ortho to the central carbon atom that was largely responsible for the enhanced fastness properties (12). That this is not the whole explanation is indicated by the fact that increased fastness properties are also exhibited by such dyes as **Setoglaucine** (Rhoduline Blue 6G) **(14)** (*C.I.* 658) and **Chrome Turquoise Blue B (15)** (2), which differ from Malachite Green in having a chloro group and a methyl group, respectively, ortho to the central carbon atom. It should be stressed that, although in general substituents ortho to the central carbon atom result in bluer greens, it is only when the substituent is a sulfo group that definite blues result.

NAPHTHALENE GREEN SERIES

If the benzene ring carrying the sulfonic acid group ortho to the central carbon atom is replaced by a naphthalene- or naphtholsulfonic acid group, green dyes of improved fastness properties are obtained. Apparently the fused second ring in naphthalene behaves like an ortho substituent. For example, **Naphtalin Green V (16)** (*C.I.* 735) has good fastness properties although the sulfonic acid groups are not ortho to the central carbon atom (11).



(16) Naphtalin Green V (*C.I.* 735)



(17) Wool Green S (*C.I.* 737)

If R salt (disodium 2-naphthol-3,6-disulfonate—see Vol. **9,** pp. 255–56) is condensed with Michler's hydrol and subsequently oxidized, **Wool Green S** (*C.I.* 737) is obtained (ref. 10, p. 307). Although formula **(17)** shows the dye made from G salt, the more valuable dye is the one from R salt.

These dyes of the so-called Naphthalene Green series are more important than other acid greens and are rapidly replacing them.

Triaminotriarylmethane Dyes (Fuchsine, Rosaniline, or Magenta Series)

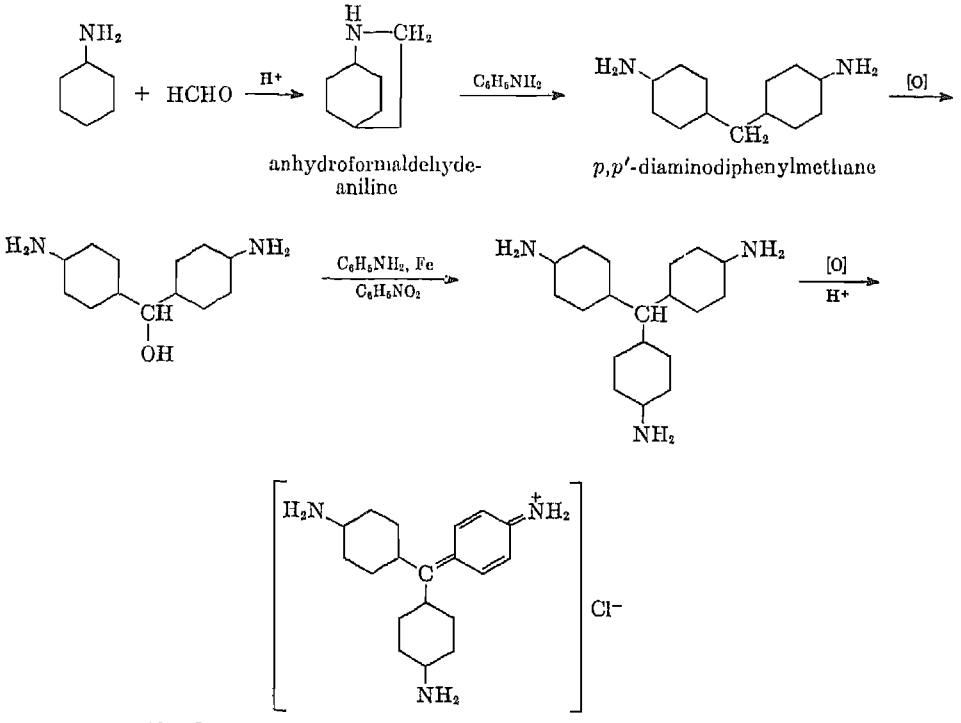
This is by far the most important group of triphenylmethane dyes. The Fuchsine derivatives may be classed as follows: (*1*) acid Fuchsines, (*2*) phenylated Fuchsines or

Spirit Blues, (*3*) sulfonated Spirit Blues or alkali-soluble blues, (*4*) alkylated Fuchsines, (*5*) Victoria Blues, (*6*) sulfonated alkylated Fuchsines (Acid Violets).

The prototype of this group is **Para Magenta** (Parafuchsine, Pararosaniline) **(18)** (*C.I.* 676), obtained originally from aniline and *p*-toluidine.

Since the starting materials for these dyes have been in many cases mixtures of closely related amines, the products have also been mixtures. As a consequence, names such as "Fuchsine" and "Rosaniline" are used somewhat loosely, and the formula assigned a dye may represent only the chief component of a mixture. Thus, the product obtained originally from aniline and *p*-toluidine has sometimes been called simply Fuchsine or Rosaniline instead of the more precise Parafuchsine or Pararosaniline. (Pararosaniline is restricted by some to the base, Pararosaniline hydrochloride or Parafuchsine being used for the salt **(18)**.) The mixed product obtained from aniline and a mixture of *o*- and *p*-toluidine ("aniline oil for red"), often represented as the monomethylated product, is properly called Fuchsine (Rosaniline, Homofuchsine, Magenta **(19)** (*C.I.* 677)). This confusion in names and formulas carries on to the various classes of derivatives.

SCHEME 12

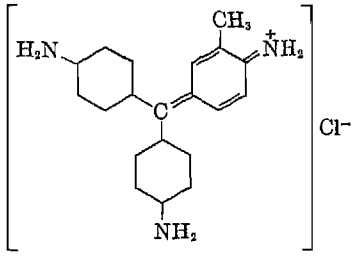


(18) Para Magenta (Parafuchsine, Pararosaniline) (*C.I.* 676)

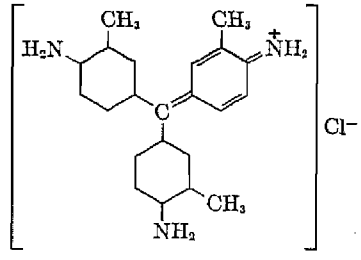
Many methods have been described for the manufacture of Parafuchsine (and other Fuchsines) but actually only two ever achieved any practical importance:

(*1*) Oxidation of a mixture of two moles of aniline and one mole of *p*-toluidine by arsenic acid, nitrobenzene, etc. This method is rarely used in the U.S., but a modification is probably used in Germany. This fusion utilizes a cheap, technical mixture of the *o*-, *p*-, and *m*-toluidines and -nitrotoluenes, together with aniline, zinc chloride and ferrous chloride. The crude product is crystallized to give a relatively pure Parafuchsine (ref. 8, Vol. **2**, p. 330).

(*2*) Formation of a diaminodiphenylmethane from aniline and formaldehyde, followed by oxidation in the presence of aniline (*Homolka's method*) (Scheme 12). This method gives higher yields of dye having a uniform composition. If *o*-toluidine is used in place of aniline in the above reaction, the supposedly trimethylated **New Fuchsine (20)** (*C.I.* 678) is formed. A mixture of *o*-toluidine and aniline gives **Homofuchsine** (*C.I.* 677), which is a mixture of Parafuchsine and its mono- and dimethyl derivatives. In all these reactions the oxidation may also be carried out exclusively with air (32).



(**19**) Fuchsine (Rosaniline) (*C.I.* 677)



(**20**) New Fuchsine (*C.I.* 678)

The chief product of commerce is now Parafuchsine, which is used for dyeing silk, wool, and paper and as a biological stain, but finds its main use in the preparation of Alkali Blues. New Fuchsine and Homofuchsine are used in the paper and lake trade.

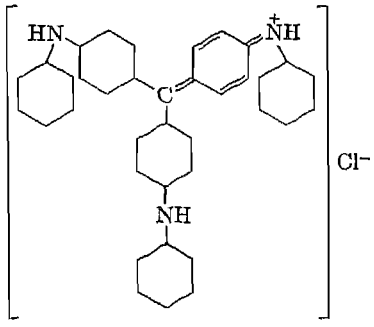
ACID FUCHSINES

Sulfonation of the Fuchsines with fuming sulfuric acid gives the Acid Fuchsines, in which the sulfonic acid groups must be meta to the central carbon atom because of the alkali sensitivity of the resulting dyes. The only member on the market is **Acid Fuchsine** (Acid Magenta), which is essentially the trisulfonic acid obtained from Parafuchsine, but is usually represented as *C.I.* 692, from Fuchsine or a mixture of Fuchsine and Parafuchsine. It finds little or no use for wool dyeing but is used as a biological stain (see Vol. **12,** p. 750), as an antihalation dye in photographic films, and as an anticaking agent for ammonium nitrate.

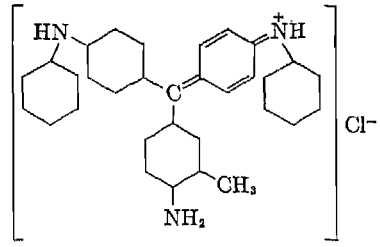
PHENYLATED FUCHSINES (SPIRIT BLUES)

The *N*-phenylated Fuchsines or Spirit Blues (Aniline Blues) contain varying amounts of mono-, di-, and triphenylfuchsines depending on the shade desired: with increasing number of phenyl groups, the shade changes from reddish to greenish. The phenylations are controlled to match the shade of an established standard. The dyes are prepared by heating Parafuchsine (or (Homo)fuchsine) with aniline in the presence of a small amount of benzoic acid. Up to three phenyl groups can be introduced into Parafuchsine, but only two into (Homo)fuchsine, as shown in the formulas for **Spirit Sky Blue** (Spirit Blue) **(21)** (*C.I.* 688), from Parafuchsine, and **Spirit Blue (22)** (*C.I.* 689), from Fuchsine. Approximately diphenylated Parafuchsine is produced in much larger amounts than the triphenylated derivative because the reddish shades are stronger than the greenish.

As the name implies, the Spirit Blues are alcohol-soluble, and they were used formerly for the coloring of spirit varnishes. Today they are prepared from Parafuchsine only for conversion to their sulfonic acids.



(21) Spirit Sky Blue (*C.I.* 688)

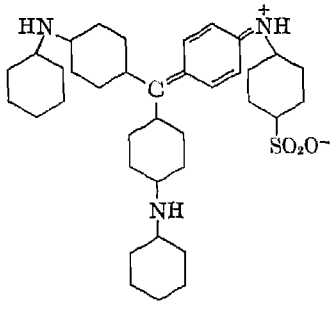


(22) Spirit Blue (*C.I.* 689)

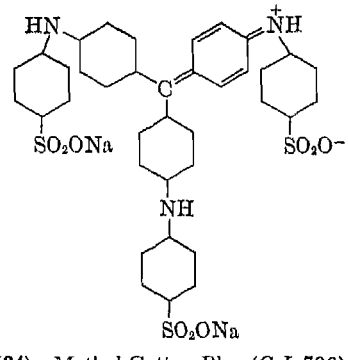
SULFONATED SPIRIT BLUES

The far more important Sulfonated Spirit Blues or Alkali-Soluble Blues (*C.I.* 703–707) are readily prepared by sulfonation of the phenylated products with concentrated sulfuric acid. Their solubility varies with the degree of sulfonation, that is, whether they contain one, two, or three sulfonic acid groups in the new phenyl groups. Because the phenylated products and likewise their sulfonated products are mixtures, the designations of the dyes are very ambiguous; furthermore, some names, *C.I.* numbers, and formulas for derivatives of Fuchsine or a mixture of Fuchsine and Parafuchsine are still given today, whereas the present commercial products are presumably derived chiefly from phenylated Parafuchsines. In general, the monosulfonic acids, which may also contain some disulfonic acids, are called *Alkali Blues* and are used in large amounts in printing inks (see Vol. **10,** p. 684); the commercial products are essentially **Alkali (Sky) Blue (23)** (*C.I.* 703) (ref. 38, p. 186) or the corresponding monosulfonic acid of diphenylated Parafuchsine.

The so-called disulfonic acids from phenylated Parafuchsines, which are probably mostly disulfonic acids with perhaps a little trisulfonic, are the *Soluble Blues* (as *C.I.* 705). They are used as their sodium salts for laundry blues and for blueing paper.



(23) Alkali Sky Blue (*C.I.* 703)



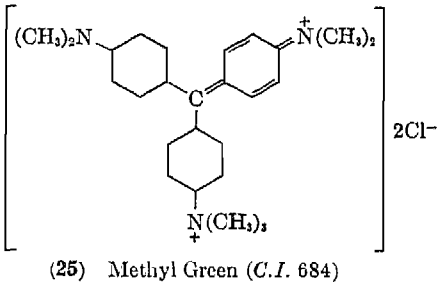
(24) Methyl Cotton Blue (*C.I.* 706)

The more highly sulfonated *Ink Blues* (Acid Ink Blue, Water Ink Blue) are probably chiefly trisulfonic acids. The largest commercial items are often designated *Soluble Blue* (Water-Soluble Aniline Blue) (*C.I.* 707) and wrongly represented as derived from diphenylated Fuchsine or Fuchsine-Parafuchsine. Actually they must be approximately the same as **Methyl Cotton Blue** (Methyl Blue, Soluble Sky Blue) **(24)** (*C.I.* 706) from triphenylated Parafuchsine, or the corresponding trisulfonic acid

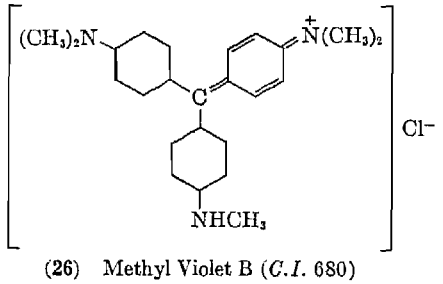
from diphenylated Parafuchsine (equivalent to *C.I.* 707 without the Fuchsine methyl group). The trisulfonic acids, usually as ammonium salts, are used in writing ink (see Vol. **7**, p. 872) and as biological stains (see Vol. **12**, p. 751).

ALKYLATED FUCHSINES

The most important Fuchsine derivatives are the *N*-alkylated Fuchsines. Hofmann, during his researches on triphenylmethanes, showed that the hydrogens of the amino groups in the Fuchsines can be replaced by methyl or ethyl groups. Direct alkylation, that is, treating Fuchsines with methyl or ethyl halides, yielded a mixture of mono-, di-, and trialkylated Fuchsines which was sold under the name of **Hofmann's Violet** (*C.I.* 679) (the original Hofmann's Violet was the triethyl derivative of Fuchsine). If the product was further alkylated, a quaternary ammonium salt such as Methyl Green **(25)** (*C.I.* 684) was formed. Although this dye is no longer of any technical importance, having been replaced by the cheaper Malachite Green, it illustrates the transformation of a dye of the Fuchsine series into a green dye similar to those of the Malachite Green class by the quaternization of one of the amino groups.



(25) Methyl Green (*C.I.* 684)

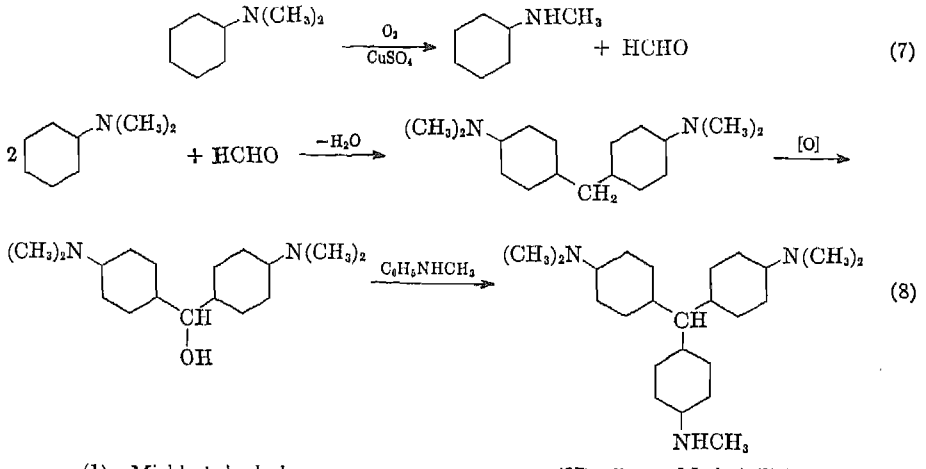


(26) Methyl Violet B (*C.I.* 680)

In an attempt to find a new method for the preparation of Hofmann's Violet, Lauth oxidized dimethylaniline and obtained a violet of much bluer shade. Later, Bandy worked out a practical method for obtaining this dye and showed that it consisted essentially of pentamethylparafuchsine, introduced as **Methyl Violet B (26)** (*C.I.* 680), or Violet de Paris. Methyl Violet is made by a different process from any other triphenylmethane dye. Dimethylaniline is oxidized by air in the presence of copper sulfate as a catalyst, with phenol and a large amount of salt (NaCl). This gives rise to *N*-methylaniline and formaldehyde (Scheme 13, eq. (7)). The formaldehyde so formed reacts with the excess dimethylaniline present to give tetramethyldiaminodiphenylmethane, which is then oxidized to Michler's hydrol (see p. 310). The hydrol, upon condensing with the *N*-methylaniline formed in eq. (7), gives rise to the **leuco base of Methyl Violet (27)** (eq. 8), which is then oxidized to the dye. These reactions all take place within the same reactor; obviously if some dimethylaniline reacts with Michler's hydrol, a product will be obtained with one more methyl group (Crystal Violet). Because of these side reactions, the Methyl Violet of commerce is usually a mixture.

Methyl Violet is sold in enormous quantities for printing inks (see Vol. **11**, p. 152), paper dyeing, hectograph inks, typewriter ribbons, and duplicating papers. Methyl Violet base can be prepared by the neutralization of the dye with sodium hydroxide. The dye itself in weak acid solution forms valuable lakes with phosphomolybdotungstic acid (see Vol. **10**, p. 675).

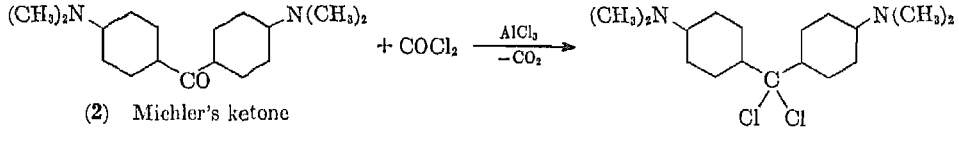
SCHEME 13



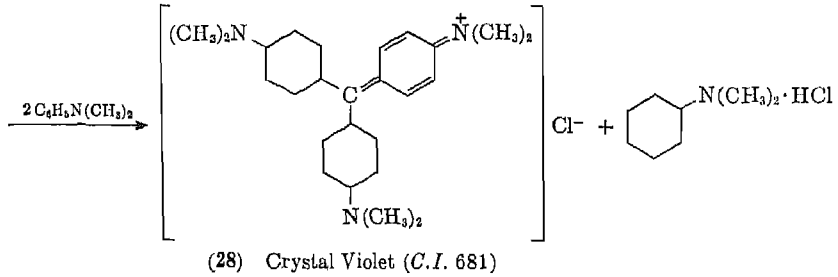
(1) Michler's hydrol (27) Leuco Methyl Violet

The next higher homolog of Methyl Violet is **Crystal Violet (28)** (*C.I.* 681). The method used for its manufacture is based on Michler's observation during his work on the preparation of tetramethyldiaminobenzophenone (see p. 310) that a small quantity of an intense violet substance was formed during the reaction of phosgene with dimethylaniline. However, it remained for Kern and Caro to recognize the importance of this side reaction. They showed that if anhydrous aluminum chloride or zinc chloride is present during the formation of the ketone, the reaction does not stop at the ketone stage but proceeds to dye formation (see Scheme 14).

SCHEME 14



(2) Michler's ketone



(28) Crystal Violet (*C.I.* 681)

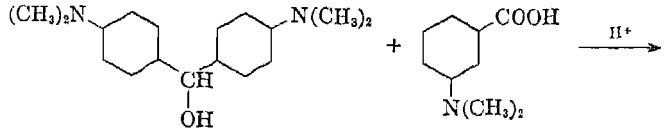
Similarly **Ethyl Violet** (*C.I.* 682) is formed if tetraethyldiaminobenzophenone is used in place of the methyl analog.

The production of Crystal Violet is about half that of Methyl Violet, and the uses are similar.

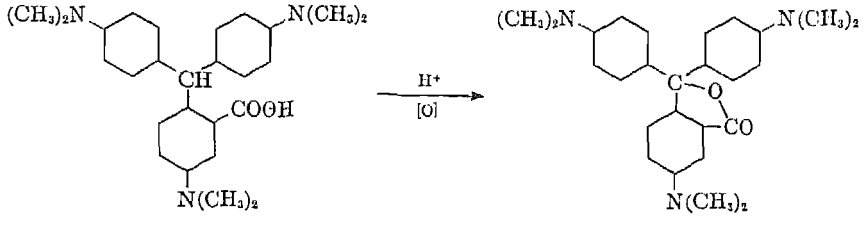
Other methods for the preparation of *N*-alkylated Parafuchsines were also discovered by Kern and Caro. For example, Michler's hydrol condenses very readily

with tertiary amines to give *N*-hexaalkylated leuco bases, which in turn are oxidized to the corresponding Parafuchsines. This general method has recently been applied to the preparation of the so-called **Crystal Violet Lactone** (3,3-bis(*p*-dimethylaminophenyl)-6-dimethylaminophthalide) **(29)** from *m*-dimethylaminobenzoic acid (Scheme 15) (23a). This lactone finds use in the manufacture of a novel type of colorless copying paper (31,33,34).

SCHEME 15



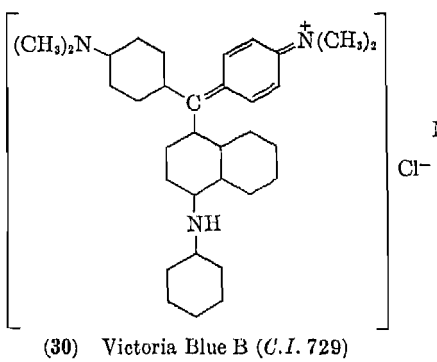
(1) Michler's hydrol



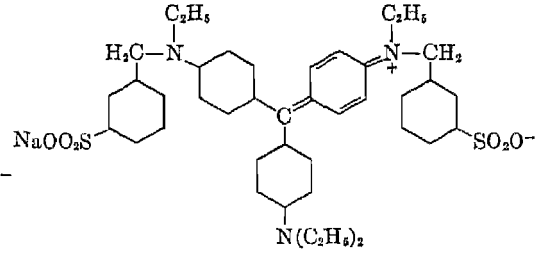
(29) Crystal Violet Lactone

VICTORIA BLUES

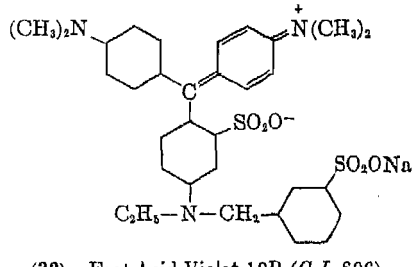
N-Alkylated Parafuchsine dyes can also be formed by reaction of Michler's ketone with an arylamine in the presence of phosphorus oxychloride. The reaction presum-



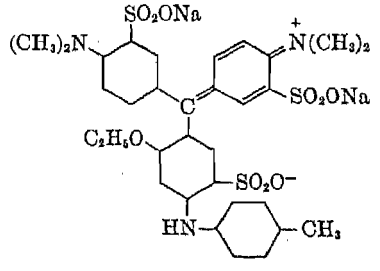
(30) Victoria Blue B (*C.I.* 729)



(31) Formyl Violet S4B (*C.I.* 698)



(32) Fast Acid Violet 10B (*C.I.* 696)



(33) Acid Violet 6B (*C.I.* 717)

ably proceeds through the intermediate formation of tetramethyldiaminobenzophenone dichloride—an extremely unstable compound. This method is used at present for the manufacture of the Victoria Blues, which are diphenylnaphthylmethane dyes.

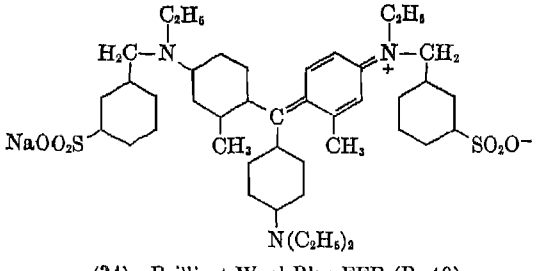
Thus, from *N*-phenyl-1-naphthylamine and Michler's ketone there is obtained **Victoria Blue B (30)** (*C.I.* 729). **Victoria Blue R** (*C.I.* 728) is the analog from *N*-ethyl-1-naphthylamine, and **Victoria Blue 4R** (*C.I.* 690) that from *N*-phenyl-*N*-methyl-1-naphthylamine. If tetraethyl-*p,p'*-diaminobenzophenone is condensed with *N*-ethyl-1-naphthylamine, the important **Victoria Pure Blue B** (Pr. 198) is formed.

The Victoria Blues, in spite of their poor lightfastness, are highly prized for the dyeing of wool and silk because of their royal blue shades.

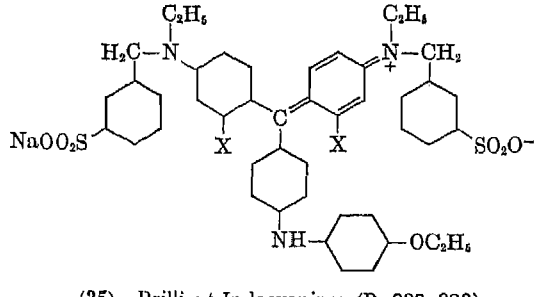
ACID VIOLETS

Sulfonic acid derivatives of the alkylated Fuchsines are valuable wool dyes, the so-called Acid Violets. The sulfonic acid groups are introduced by methods similar to those used in the Malachite series (see p. 313). The most important members of the Acid Violets are **Formyl Violet S4B (31)** (*C.I.* 698), **Fast Acid Violet 10B (32)** (*C.I.* 696), and **Acid Violet 6B (33)** (*C.I.* 717). (The sulfonic acid groups correctly shown here as meta in *C.I.* 698 and 696, are shown as para in the *Colour Index*. In addition to *C.I.* 698, a different Formyl Violet is made at present by using dimethylaniline instead of diethylaniline in the final condensation. Another Acid Violet 6B (FD&C Violet No. 1, *C.I.* 697) also has meta, not para, sulfonic acid groups.) Fast Acid Violet 10B, with a sulfo group ortho to the central carbon atom, is fast to alkali, whereas Formyl Violet is not fast to alkali.

Introduction of two methyl groups ortho to the central carbon atom in Formyl Violet changes this dye from a violet to a blue, **Brilliant Wool Blue FFR (34)** (Pr. 40).



(34) Brilliant Wool Blue FFR (Pr. 40)



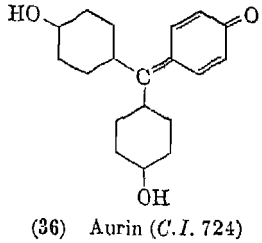
(35) Brilliant Indocyanines (Pr. 222, 223)

Fastness to light in this series has been achieved by modifying the molecule so that a *p*-alkoxydiphenylamine structure is present (25). Two important dyes are

produced in this way: **Brilliant Indocyanine 6B-CF** (Pr. 222) (**35**, X = hydrogen) and **Brilliant Indocyanine G** (Pr. 223) (**35**, X = methyl).

The Hydroxytriarylmethanes (Rosolic Acid Series)

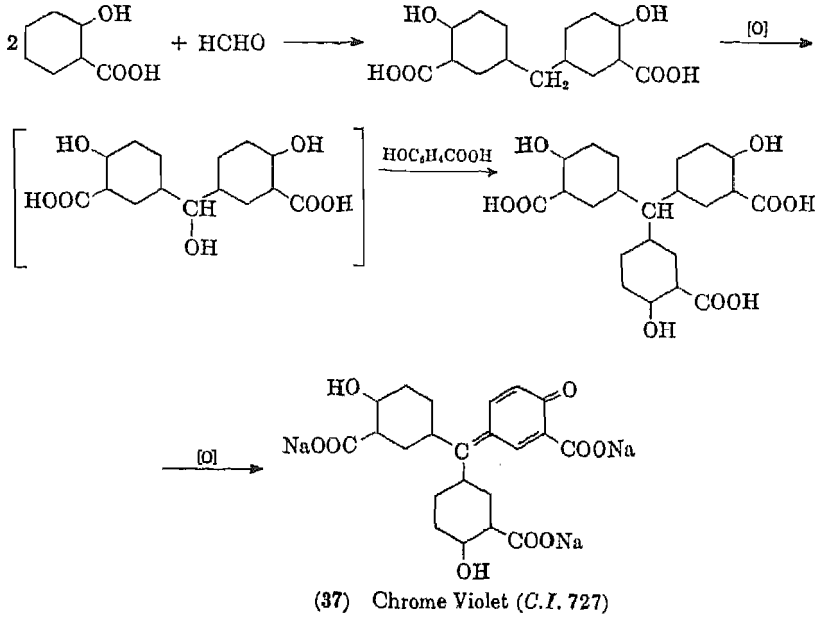
Aurin (rosolic acid) **(36)** (*C.I.* 724) is the prototype of this series but has no technical significance as a dye in spite of its deep red color. Two grades, one with m.p. 308–10°C. (decompn.) and a practical grade, which may be yellowish-brown, are commercially available for use as a dye intermediate.



(36) Aurin (*C.I.* 724)

The first member of this series, **Chrome Violet** (aurintricarboxylic acid) **(37)** (*C.I.* 727) was prepared by Sandmeyer by heating salicylic acid and formaldehyde with concentrated sulfuric acid, followed by oxidation with nitrosylsulfuric acid. Presumably the reaction proceeds as shown in Scheme 16.

SCHEME 16

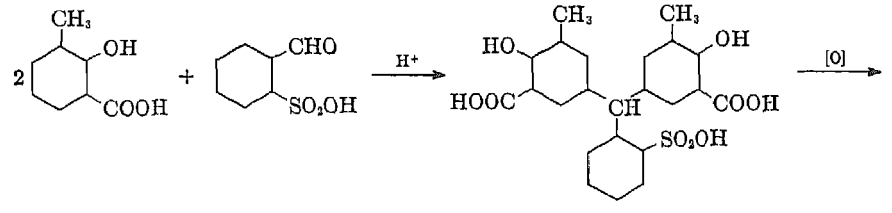


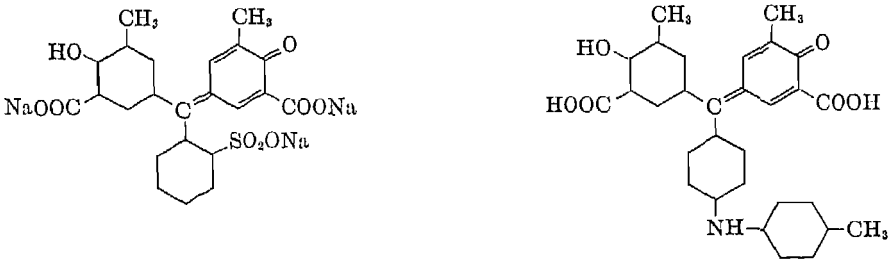
(37) Chrome Violet (*C.I.* 727)

Chrome Violet is a chrome mordant dye for cotton, giving pretty, reddish-violet shades not too fast to light. In fact, this lack of lightfastness is a characteristic of the group as a whole. The triammonium salt, *Aluminon*, is used in analysis, especially for aluminum, with which it forms a red lake.

Generally, *o*-cresotinic acid (2,3-cresotic acid) is used in place of salicylic acid since the dye from the latter shows only slight change on chroming. The central carbon atom may be furnished by an aromatic aldehyde instead of by formaldehyde, as in the use of benzaldehyde-*o*-sulfonic acid for the preparation of **Eriochrome Cyanine R** (Acid Chrome Cyanine R) **(38)** (*C.I.* 722) (see Scheme 17). This dye gives violet-blue shades on chroming.

SCHEME 17





(38) Eriochrome Cyanine R (*C.I.* 722)

(39)

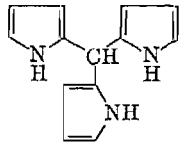
If *p*-diethylaminobenzaldehyde is used in place of benzaldehyde-*o*-sulfonic acid, **Chromoxane Cyanine RE** (Pr. 461) results. The very valuable **Eriochrome Azurol B** (Acid Chrome Azurol B) (*C.I.* 720) results from the condensation of *o*-cresotinic acid and 2,6-dichlorobenzaldehyde. It dyes wool a Bordeaux shade which is converted into blue by afterchroming.

The central carbon atom may also be furnished by Michler's hydrol, which with *o*-cresotinic acid gives **Monochrome Violet FB** (Pr. 301).

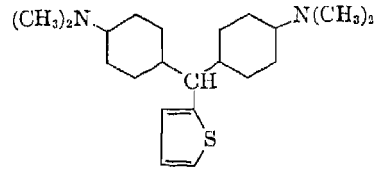
Efforts have been made to increase the lightfastness of this group by the preparation of compounds of the type of **(39)**.

Triphenylmethane-like Compounds Containing One or More Heterocylic Rings

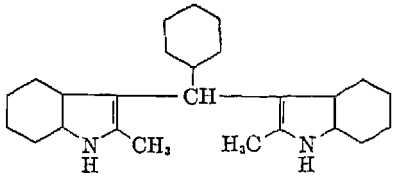
Compounds are known in which one or more of the benzene rings in triphenylmethane are substituted by a heterocyclic ring. Examples of leuco bases of this type are those containing the rings of pyrrole **(40)** (see also Vol. **11**, p. 349), thiophene **(41)** (16), indole (*q.v.*)**(42)**(7), and quinoline **(43)**(6) (see also Vol. **11**, p. 408). A series of *Rosindole dyes* have been prepared by condensation of 2-substituted indoles or indolylmagnesium halides with aldehydes and oxidation of the leuco bases in the presence of acid. They form the basis for a colorimetric estimation of many indoles; thus, 2-methylindole and *p*-dimethylaminobenzaldehyde in alcoholic solution give a red color on the addition of hydrochloric acid (20a).



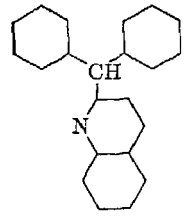
(40) Leuco Tripyrrylmethane



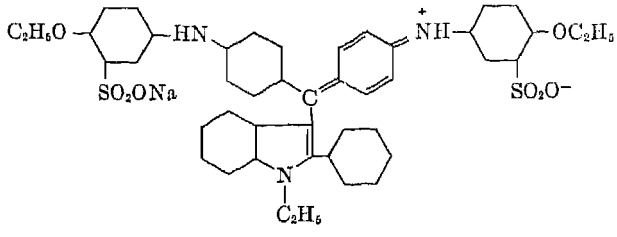
(41) Leuco Thiophene Malachite Green



(42) A Leuco Rosindole



(43) Leuco Diphenylquinolylmethane



(44) Wool Fast Blue FBL

None of these leuco heterocyclic compounds have any commercial value. However, since 1940 patents have been taken out on a number of indolyldiarylmethane acid dyes for which excellent lightfastness is claimed (1). Typical is **Wool Fast Blue FBL (44)**, which gives fast blue dyeings on silk and wool. Except for specialized uses, it is doubtful whether these dyes will ever achieve commercial importance, principally because of their high cost.

Moth Inhibitors of the Triphenylmethane Series

The triphenylmethane moth inhibitors, as well as the triphenylphosphine derivatives, are notable for their effectiveness throughout the normal life of the fabric (see Vol. **13,** p. 904). The triphenylmethanes are more effective than all other known moth inhibitors (except Mitin FF, a derivative of diphenylurea, and Eulan NK, a tetraphenylphosphonium salt) because they combine the characteristics of a moth inhibitor and a dye. Although they are "colorless dyes," they can be applied to wool similarly to dyes, even during the dyeing operation (37a).

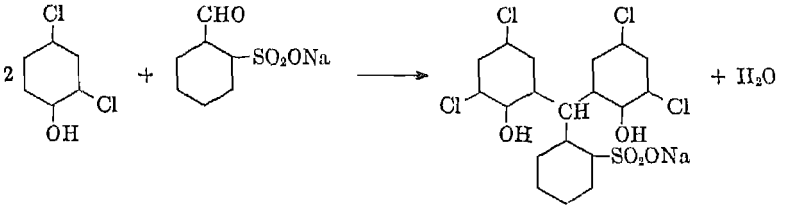
History. The systematic research that led to the discovery of these valuable moth inhibitors had its beginning in the saying among German housewives that cloth dyed green was never attacked by moths. E. Meckbach, working in the laboratories of the Bayer Company, found that this was actually true; the yellow component used to produce green dyeings was *Martius Yellow* (2,4-dinitro-1-naphthol), which did, in fact, mothproof wool (17). At first, Meckbach had high hopes that he could produce a range of dyes that would make wool mothproof. Although literally thousands of dyes were subsequently investigated, none proved to be as effective as Martius Yellow. Minaeff also investigated the use of dyes for this purpose and came up with equally discouraging results (18).

However, Meckbach's researches led to the discovery that any inorganic compound containing fluorine will mothproof wool. In 1920 the Bayer Company came out with a series of fluoro compounds as mothproofers, under the name "Eulans." The use of fluoro compounds, however, was far from satisfactory, principally because of the difficulties encountered in application and the very poor wash fastness of such compounds.

In 1928, the I. G. Farbenindustrie placed on the market the first of the colorless triphenylmethane dyes with excellent moth-inhibiting qualities, under the name Eulan N (Eulan Neu).

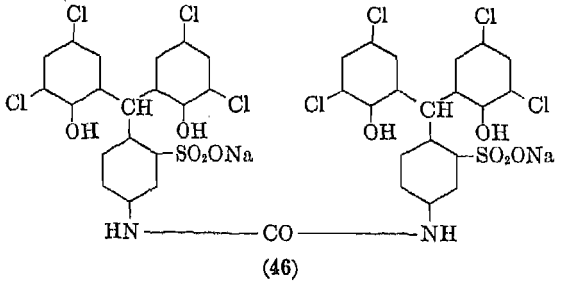
Eulan N (2,2′-dihydroxy-3,5,3′,5′-tetrachlorotriphenylmethane-2″-sodium sulfonate, sodium α,α-bis(3,5-dichloro-2-hydroxyphenyl)-*o*-toluenesulfonate) **(45)** is manufactured by condensing 2,4-dichlorophenol with the sodium salt of benzaldehyde-*o*-sulfonic acid (24) (see Scheme 18). This is a general reaction for the preparation of compounds of this type.

SCHEME 18

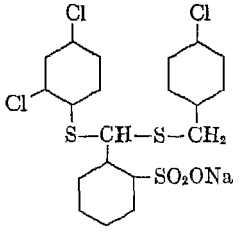


(45) Eulan N

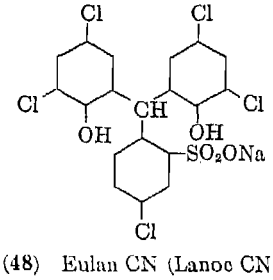
Many modifications of the Eulan N structure were studied. Isomers were prepared, more chlorine and additional sulfonic acid groups were introduced into the molecule, and esters and ethers were prepared (20). The relation between chemical structure and mothproofing effect was also investigated on dihydroxydi(and tri)phenylmethanes and their chloro derivatives (16a).



(46)



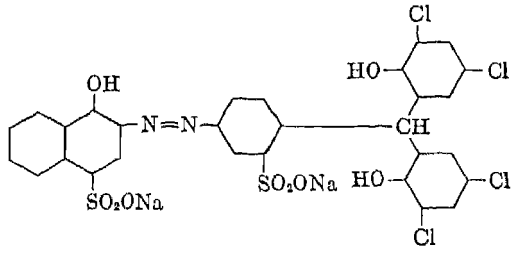
(47)



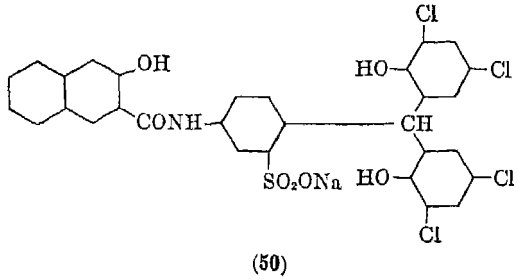
(48) Eulan CN (Lanoe CN)

Such varied structures as **(46)** (ref. 22, frame 802) and **(47)** (20) were also examined. The only modification of the Eulan N structure that proved to be of commercial value was the introduction of a chlorine group meta to the sulfonic acid group to give the agent **(48)**, marketed by the I.G. in 1934 as **Eulan CN** (20), and three years after World War II by Imperial Chemical Industries, Ltd., as **Lanoc CN.** Eulan CN has twice the moth-inhibiting properties of Eulan N.

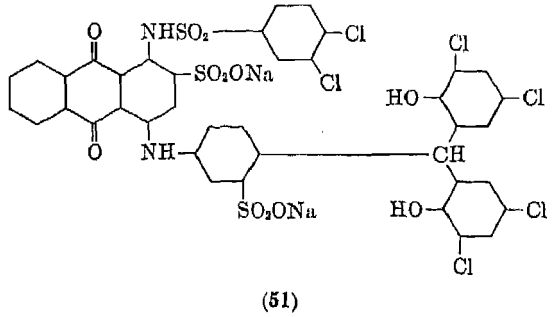
Although Meckbach was unable to find a range of dyes with mothproofing properties, the I.G. actually prepared such products about 1940. This was accomplished by introducing the fundamental Eulan N structure into well-known dye structures. For this purpose amino Eulan N was prepared by the condensation of 2,4-dichlorophenol with the sodium salt of *p*-aminobenzaldehyde-*o*-sulfonic acid (ref. 22, frame 768). From this amino compound, by conventional reactions, were prepared repre-



(49)



(50)



(51)

sentatives of various types of dyes, for example, azo **(49)** (ref. 22, frame 805), Naphthol AS **(50)** (ref. 22, frame 807), anthraquinone **(51)** (ref. 22, frame 808), and triphenylmethane dyes. It is doubtful whether these dyes will ever achieve commercial im-

portance as mothproofers. Aside from their high cost, sufficient mothproofing can only be obtained with the deep shades.

Bibliography

(1) *BIOS, Final Rept.* 959 (Manufacture of Triphenylmethane Dyestuffs and Intermediates at Ludwigshafen and Hoechst).
(2) *BIOS, Final Rept.* 1433 (Manufacture of Triphenylmethane Dyestuffs at Hoechst, Ludwigshafen and Leverkusen).
(3) Blangey, L., Fierz-David, H. E., and Stamm, G., *Helv. Chim. Acta*, **25**, 1162 (1942).
(4) Bowman, R. E., and Stroud, H. H., *J. Chem. Soc.*, **1950**, 1432.
(5) Davies, R. R., and Hodgson, H. H., *J. Soc. Dyers Colourists*, **59**, 196 (1943).
(6) Dey, A. N., and Dutt, S., *J. Indian Chem. Soc.*, **5**, 535 (1929).
(7) Elderfield, R. C., *Heterocyclic Compounds*, Wiley, N.Y., 1952, Vol. III, p. 76.
(8) *FIAT* 1313 (German Dyestuffs and Dyestuffs Intermediates).
(9) Fierz-David, H. E., *Kunstliche Organische Farbstoffe*, Springer, Berlin, 1926, Vol. III, ch. 7.
(10) Fierz-David, H. E., and Blangey, L., *Fundamental Processes of Dye Chemistry*, 5th ed., Interscience, N.Y., 1949.
(11) Frisch, F., *Helv. Chim. Acta*, **13**, 768 (1930); **14**, 669 (1931).
(12) Hagenbach, H., *Helv. Chim. Acta*, **6**, 165 (1923).
(13) Kehrmann, F., *Helv. Chim. Acta*, **10**, 670 (1927).
(14) Kehrmann, F., Roy, G., and Ramm, M., *Helv. Chim. Acta*, **5**, 153 (1922).
(15) Liston, T. R., and Dehn, W. M., *Ind. Eng. Chem.*, **26**, 1073 (1934).
(16) Mason, C. D., and Nord, F. F., *J. Org. Chem.*, **16**, 723 (1950).
(16a) Matsui, K., *J. Soc. Org. Synthetic Chem. (Japan)*, **9**, 92 (1951); *C.A.*, **47**, 815.
(17) Meckbach, E., *Melliand Textilber.*, **2**, 350 (1921).
(18) Minaeff, M. G., *Textile Colourists*, **49**, 89 (1927).
(19) Ramart-Lucas, P., *Bull. soc. chim. (France)*, **12**, 472 (1945).
(20) Stoetter, H., *Z. angew. Chem.*, **59**, 145 (1947).
(20a) Sumpter, W. C., and Miller, F. M., *Heterocyclic Compounds with Indole and Carbazole Systems*, Interscience, N.Y., 1954, pp. 48, 60.
(21) Tomioka, I., *J. Soc. Chem. Ind., Japan*, **34**, 176B (1931).
(22) Vogt *et al.*, Office Tech. Services Rept. **PB-74893**, April 17, 1940. Conference on Eulan, Frames 762–817.
(23) Wizinger, R., *Ber.*, **60**, 1377 (1927).
(23a) U.S. Reissue 23,024 (Aug. 17, 1948), C. S. Adams (to National Cash Register Co.).
(24) U.S. Pat. 1,707,181 (March 26, 1929), M. Weiler, B. Wink, and H. Stoetter (to General Aniline).
(25) U.S. Pat. 1,731,637 (Oct. 15, 1930), H. Polikier and O. Boeger (to General Aniline).
(26) U.S. Pat. 2,032,033 (Feb. 25, 1936), P. H. Wolff (to General Aniline).
(27) U.S. Pat. 2,154,926 (April 18, 1939), P. H. Wolff, F. Heim, C. Winter, and L. Bettag (to General Aniline).
(28) U.S. Pat. 2,198,298 (April 23, 1940), P. H. Wolff and F. Heim (to General Aniline).
(29) U.S. Pat. 2,202,037 (May 28, 1940), P. H. Wolff and E. Beniers (to General Aniline).
(30) U.S. Pat. 2,231,067 (Feb. 11, 1941), P. D. Hammond and R. W. Harris (to Heyden Chemical Corp.).
(31) U.S. Pat. 2,505,470 (April 25, 1950); U.S. Pat. 2,505,472 (April 25, 1950), B. K. Green (to National Cash Register Co.).
(32) U.S. Pat. 2,542,544 (Feb. 20, 1951), S. A. Loukomsky and G. S. Herrick (to American Cyanamid Co.).
(33) U.S. Pat. 2,548,364–6 (April 10, 1951), B. K. Green and R. W. Sandberg (to National Cash Register Co.).
(34) U.S. Pat. 2,618,573 (Nov. 18, 1952), B. K. Green (to National Cash Register Co.).

GENERAL REFERENCES

(35) Bucherer, H., *Lehrbuch der Farbenchemie*, 2nd ed., Otto Spamer, Leipzig, 1921, pp. 295–312.
(36) Fischer, E., *Untersuchungen über Triphenylmethanfarbstoffe*, Springer, Berlin, 1924.
(37) Gilman, H., *Organic Chemistry*, Wiley, N.Y., 1953, Vol. III, pp. 294–312.

(37a) Moncrieff, R. W., *Mothproofing*, Leonard Hill, Ltd., London, 1950.
(38) Pratt, L. S., *The Chemistry and Physics of Organic Pigments*, Wiley, N.Y., 1947, ch. 8.
(39) Venkataraman, K., *The Chemistry of Synthetic Dyes*, Academic Press, N.Y., 1952, Vol. II, ch. 23.
(40) U.S. Pats.: Class 260, Sub-Classes 387 through 394; 570.

A. J. COFRANCESCO

4,4′,4″-TRIPHENYLMETHANE TRIISOCYANATE, $CH(C_6H_4NCO)_3$. See *Phosgene (organic isocyanates)*, Vol. **10,** pp. 399, 401.

TRIPHENYL PHOSPHATE, $(C_6H_5)_3PO_4$. See *Plasticizers*, Vol. **10,** p. 780.

TRIPLE SUPERPHOSPHATE. See *Fertilizers*, Vol. **6,** p. 419.

TRIPOLI. See *Abrasives*, Vol. **1,** p. 4.

TRIPTANE, $(CH_3)_3CCH(CH_3)_2$. See "2,2,3-Trimethylbutane" under *Hydrocarbons*, Vol. **7,** pp. 603, 640.

TRISACCHARIDES. See *Sugars (survey)*.

TRIS(2-CHLOROETHYL)AMINE, $(ClH_2CCH_2)_3N$. See *Gas warfare agents*, Vol. **7,** p. 128.

TRITIUM, T. See *Hydrogen*, Vol. **7,** p. 677; *Water*.

TRITOLYL PHOSPHATE, $(CH_3C_6H_4)_3PO_4$. See "Tricresyl phosphate" under *Plasticizers*, Vol. **10,** p. 782.

TRITONAL. See *Explosives (high)*, Vol. **6,** p. 56.

TRITYLATION

Introduction of the trityl (triphenylmethyl) group, $(C_6H_5)_3C$—.

TROCHES. See *Pharmaceuticals*, Vol. **10,** p. 230.

TROEGER'S BASE, $C_{17}H_{18}N_2$. See *Schiff bases*, Vol. **12,** pp. 110, 111.

TRONA, $Na_2CO_3.NaHCO_3.2H_2O$. See *Sodium compounds*, Vol. **12,** p. 601.

TRONA PROCESS. See *Boron compounds*, Vol. **2,** p. 611.

TROOSTITE. See *Steel*, Vol. **12,** p. 830.

TROPACOCAINE, $C_{15}H_{19}NO_2$. See *Alkaloids*, Vol. **1,** p. 480.

TROPAEOLIN O; TROPAEOLIN OO. See *Indicators*, Vol. **7,** p. 805.

TROPICAL BLEACH. See *Chlorine compounds, inorganic*, Vol. **3,** p. 689.

TROPINE, $C_8H_{15}NO$; **TROPEINES.** See *Alkaloids*, Vol. **1,** p. 479.

TRUB. See *Beer and brewing*, Vol. **2,** p. 395.

TRUXILLINES, $C_{38}H_{46}N_2O_8$. See *Alkaloids*, Vol. **1,** p. 481.

TRYPANOCIDES

Agents having value in the destruction of trypanosomes are known as trypanocides or trypanosomicides. The parasites involved are spindle-shaped, flagellated protozoa, which belong to the genus *Trypanosoma* of the family Trypanosomidae in the class Mastigophora. These organisms occur in fish, amphibians, reptiles, birds, and mammals, sometimes causing apparently symptomless infections, but usually marked pathological changes take place in the host and death may result. The trypanosomes of man and other mammals most frequently invade the bloodstream as the result of a bite of an infected insect. In the case of *Trypanosoma equiperdum*, the need for an intermediate insect host has been lost, and the parasite is transferred directly by infected horses during coitus. Hoare (89,90) has discussed the interrelationships of hemoflagellates and the systematic classification of mammalian trypanosomes.

Biology of Mammalian Trypanosomes

The trypanosomal parasites of man include *Trypanosoma gambiense, T. rhodsiense, T. cruzi,* and *T. ariarii.* The first two organisms, which are transmitted by the bite of *Glossina,* the tsetse fly, cause forms of African sleeping sickness (not to be confused with the virus-caused encephalitides). These organisms are transmitted by inoculative means, having developed in the salivary glands of the intermediate insect host (anterior development). Both of these species of trypanasomes occur in the blood and lymph in early stages of the infections and later pass through the cerebral capillary walls (blood-brain barrier) to invade the brain tissue and cerebrospinal fluid. If untreated, this encephalitis leads to prolonged comatose states and eventual death. The infections caused by *T. rhodesiense* are more rapid in clinical course than those involving *T. gambiense.*

T. cruzi is the causative agent of Chagas' disease, sometimes called South American trypanosomiasis. It is transmitted by the exposure of an open wound (as from an insect bite) or the mucous membranes to the feces of infected reduviid ("kissing") bugs; this is called transmission by contaminative means. The trypanosomes undergo development in the posterior portion of the alimentary tract of the insects. *T. cruzi* attacks the reticuloendothelial system (a result of the form of the parasite), as well as other tissues and the bloodstream and produces an inflammatory condition, which is most often chronic. Involvement of the cardiac muscles may cause death, especially in young children, who are outstandingly susceptible to the disease.

T. ariarii was discovered near Bogotá in Colombia and was reported as a human parasite in 1951 (23). Relatively little is known concerning this organism, which might be the same as the rat trypanosome, *T. lewisi,* reported from the Federated Malay States in 1933. There are a number of sources of information on the human trypanosomiases, both with respect to the parasites and the clinical aspects of the diseases produced (83,85,87,90).

Although greater interest is ordinarily attached to diseases directly affecting man, the impact of a number of trypanosomal diseases of animals upon world economy is of considerable significance. Among the more destructive of the trypanosomes causing infections of man's animals are: *T. evansi* (surra; the diseases known as murrina and derrengadera, once considered to be due to *T. hippicum* and *T. venezuelense,* appear to be produced by strains of *T. evansi*); *T. brucei* (nagana); *T. cazalboui* (souma); *T. equinum* (mal de caderas); *T. equiperdum* (dourine); *T. theileri* (galziekte); and *T. congolense.* The greater number of these diseases are transmitted by insects, especially various species of the tsetse flies, which abound in much of Africa. Laboratory animals, especially rodents, have been employed in the testing of potential trypanocides. Among the parasites most frequently used for this purpose are *T. brucei, T. evansi, T. equiperdum, T. congolense,* and *T. cruzi* (50). Veterinary parasitology has been treated in its general aspects by a number of authors (83,90,93).

The biochemistry of the trypanosomes has been investigated rather well and its general aspects summarized (82,92). Certain of the findings, especially those relating to the intense aerobic glycolysis by the African trypanosomes, have proved of interest in the development of patterns of research on potential trypanocides. It is highly significant that the metabolic processes of the organisms may vary with the stages in the life cycle in the intermediate and definitive hosts (crithidial and trypanosomal forms in most cases; *T. cruzi* has a leishmanial stage in addition to these).

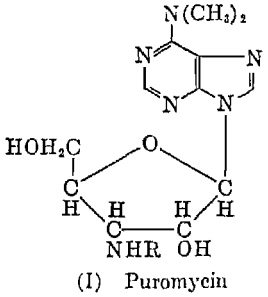
The marked differences in the several groups of trypanosomes (89,90) are particularly shown in a comparison of the trypanosomiases caused by representatives of the *lewisi* and *brucei* groups which infect man. *T. cruzi*, a parasite of the *lewisi* group, not only shows morphological and biological characteristics such as lower carbohydrate requirements which set it apart from the African trypanosomes *T. gambiense* and *T. rhodesiense* (*brucei* group), but its response to chemotherapeutic agents also highlights the differences. Therefore the discussion on trypanocidal agents is separated into two groups, because those drugs which have value in sleeping sickness fail to influence Chagas' disease and vice versa.

Chemotherapy of the African Trypanosomiases

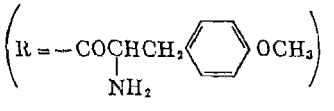
NATURAL PRODUCTS

Sleeping sickness has been a great scourge to the peoples of Africa; however, there have been few reports concerning native treatments other than those involving excision of the cervical lymph nodes (which become enlarged: Winterbottom's sign of African trypanosomiasis) or incantations (46,66). Certain remedies which have been used in Liberia have been divulged (88). Most of these are purely botanicals; however, one consists of the bark of *Newboldia laevis* roots, roasted, then beaten with peppers and cockroach dung, the mixture being rubbed into the scalp of the patient. It appears that only one preparation of botanical origin has been given (unsuccessful) trial under medical supervision (5).

The trypanocidal action of materials obtained from bacteria has been known for many years (13,37,59,68,72), but these have not proved to be of practical importance. Antibiotics from fungi, including penicillin, have no value against these hemoflagellates (48,61). There has been indication that certain *Actinomyces* produce antibiotics having action on trypanosomes (11,27,43,55,60,64,69); of these only **puromycin** (from *Streptomyces albo-niger*) and **erythromycin,** N.N.R. (from *Streptomyces erythreus*, see Vol. **13,** p. 94) seem to have activity at a potentially practical level. Puromycin has structure I (3,29,70); the related amino nucleoside (I, R=H) appears to have greater trypanocidal activity than the antibiotic (2).



(I) Puromycin

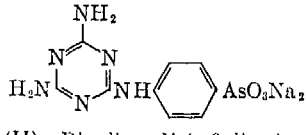


Both *epinephrine* (*q.v.*) (62) and *cortisone* (see Vol. **7,** p. 500) (16,73) exert an unfavorable effect upon trypanosome infections, by causing a more rapid increase in parasite numbers.

ARSENICALS

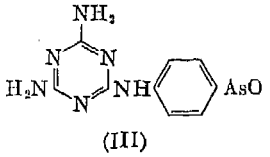
Arsenic-containing compounds represent the most thoroughly investigated class of trypanocides, and have a long and varied history of use (81,84,85,91) (see also

Arsenic preparations). Apparently, Dr. David Livingstone first suggested the use of an arsenic compound in the treatment of an animal trypanosomiasis as early as 1858. The first actual trial of an arsenical in an experimental trypanosomiasis involved the use of **atoxyl** (sodium arsanilate) in 1904. However, long before the elucidation of its structure in 1907, atoxyl was known to have serious toxic effects (especially with regard to its damage of the optic nerve). The general pattern of work in the field has centered about the aromatic arsonic acids. Among the great numbers of compounds which were investigated (81,86,91) in an effort to achieve greater effectiveness in all stages of sleeping sickness without the serious toxicity of atoxyl, **tryparsamide,** U.S.P. XIV, represented the first great advance (91). This drug was synthesized in 1919, and through the succeeding years has shown such marked worth that it still finds wide use. The Belgian government awarded a prize for the development of this drug even though its administration is not without hazards, in particular when the patient is poorly nourished. At the present time, there is another arsanilic acid derivative, **disodium *N*-(4,6-diamino-*s*-triazin-2-yl)arsanilate (Melarsen)** (II), which is being given considerable attention because of favorable chemotherapeutic index (the ratio of the curative dose to the lethal dose of the drug). It is made by the reaction of atoxyl with 2-chloro-4,6-diamino-*s*-triazine (4,17). Notwithstanding their value in early cases of African trypanosomiasis, the tendency has been to avoid the use of pentavalent arsenicals because the toxicity is great. Considerable significance may be attached to the mechanism of action of the arsonic acids through reduction *in vivo* and the combination of the resultant trivalent arsenic type with thiol groups in various enzymes (91)

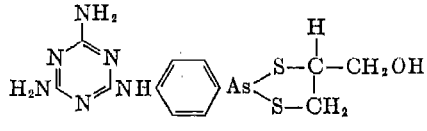


(II) Disodium *N*-(4,6-diamino-*s*-triazin-2-yl)arsanilate

4-(*p*-Arsenosophenyl)butyric acid (Butarsen, compound 70A) was one of the earlier trivalent arsenicals which showed marked antitrypanosomal action and relatively low toxicity in experimental infection. However, its value was less than desired in the clinic (91). The arsenoso compound ("arsenoxide") (III), which has been called **Melarsen oxide,** although it is prepared by the reduction of Melarsen with sulfur dioxide and hydriodic acid (4,17), has been shown to be superior to Butarsen in field trial. This arsenoxide, although considerably active against strains of trypanosomes which resist the pentavalent arsenicals, is less potent than the 2-arsa-1,3-dithiacyclopentane derivative (**Mel B,** arsobal) (IV). This latter compound has very marked trypanocidal action even in later-stage cases and causes relatively few toxic manifestations. It is prepared (80) by the reaction of the arsenoxide (III) with 2,3-dimercaptopropanol (British Anti-Lewisite, BAL).



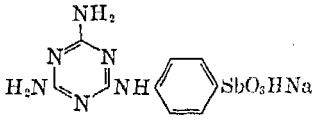
(III)



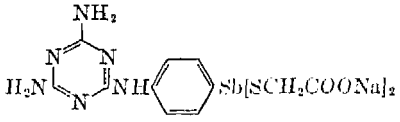
(IV)

ANTIMONIALS

Tartar emetic (antimony potassium tartrate, U.S.P. XIV) (see Vol. **2,** p. 65) was first used as a trypanocide in 1907. There was some competition in the clinical use of tartar emetic and atoxyl for a while, but it eventually became apparent that antimony compounds were not as effective in the treatment of this type of hemoflagellate infection as in leishmaniasis (81,91). Among the trypanocidal antimonials which have received serious attention in the clinic, MSb and MSb3 appear to have the most satisfactory balance of chemotherapeutic and pharmacologic properties. Both of these are melamine derivatives. **MSb** is a polymer of the sodium salt (V) of mel-



(V) Sodium *N*-(4,6-diamino-*s*-triazin-2-yl)stilbanilate (MSb)

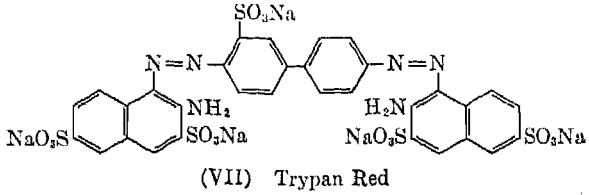


(VI) MSb3

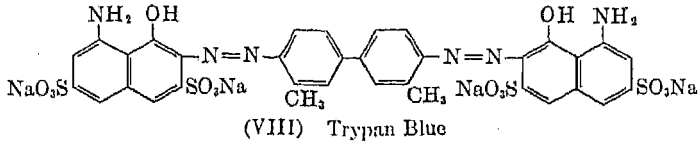
aminylstibanilic acid (*p*-(4,6-diamino-*s*-triazin-2-ylamino)benzenestibonic acid), produced by the action of urea on that compound under carefully controlled conditions (18). Melaminylstibanilic acid may be prepared by the reaction of stibanilic acid with 2-chloro-4,6-diamino-*s*-triazine, in much the same way as (II). **MSb3** (VI) is a trivalent antimony compound, which is made by the action of sodium thioglycolate on (V) (79). MSb has an extremely favorable chemotherapeutic index and shows definite prophylactic action. MSb3 resembles Melarsen oxide (III) in its behavior in the patient. Final evaluation of these antimonials must await completion of field trials. The mode of action is probably the same as that of the arsenicals.

DYES AND KINDRED DRUGS

The systematic investigation of many classes of dyes (*q.v.*) as potential chemotherapeutic agents led Ehrlich and coworkers to the discovery (91) that certain disazo dyes had some trypanocidal activity. Among this group of dyes, *Trypan Red* (*C.I.* 438) (VII) and *Trypan Blue* (*C.I.* 477) (VIII), had particularly noteworthy value. Eventually, the pattern of variations in the field led to the urea derivative **Afridol Violet** (IX), which became the point of departure into a long series of ureas. The culmination of the work was a class of nontinctorial symmetrical urea derivatives which contained naphthylaminesulfonic acid moieties.

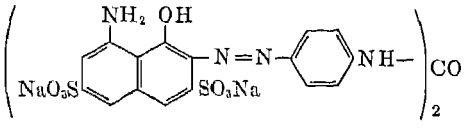


(VII) Trypan Red

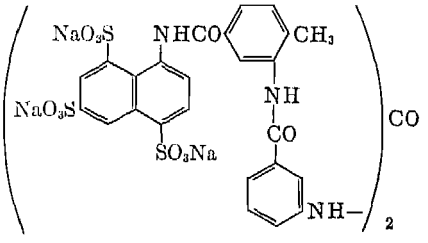


(VIII) Trypan Blue

The development of this series, which entailed the synthesis and testing of nearly 2,000 compounds, finally produced the powerful trypanocide **suramin sodium,** U.S.P. XIV, N.N.R. (Bayer 205, Fourneau 309, Naphuride sodium) (X). It is important to note that even minor variations in the structure of this complex compound result in marked decrease in activity. The drug was synthesized during World War I, and announcement was made in 1920 without divulging the structure (15,20,64,84,94). The original synthesis was accomplished by Heymann and coworkers (28). However, it was necessary for Fourneau and his collaborators (15) to reinvestigate a great portion of the field in the incisive efforts which led to the unravelling of the structure of (X). This complex urea derivative was prepared by the reaction of sodium 1-naphthylamine-4,6,8-trisulfonate with 4-methyl-3-nitrobenzoyl chloride to give a nitro



(IX) Afridol Violet



(X) Suramin sodium

amide. The nitro group was reduced and the resulting amino amide further treated with 3-nitrobenzoyl chloride to give a nitro diamide. This nitro group was then reduced, and the amino diamide converted into suramin sodium by reaction with phosgene. Suramin has high activity in early stages of several African trypanosomiases and also has noteworthy prophylactic activity of long duration. There seems to be synergism with the arsenicals, and combination treatment has been advocated. The persistence of suramin in the body is not apparently related to the trypanocidal activity; however, it may be interrelated through the ability of the drug to combine firmly with protein materials. This remarkable compound has had widespread use in both human and veterinary practice despite the fact that serious toxic side effects may occur, in particular kidney damage such as nephritis.

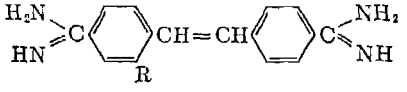
Both a mixture and a true salt of suramin with pentamidine (XIII) have been tested (see p. 335).

DIAMIDINE DRUGS

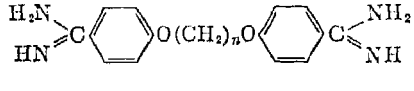
The facts that trypanosomes exhibit intense glycolysis and that **1,1′-decamethylenediguanidine** (Synthalin), $H_2N(NH{:})CNH(CH_2)_{10}NHC(:NH)NH_2$, causes hypoglycemia were the basis for a trial of this compound against *T. brucei* (30,85). It was later shown (40) that the considerable trypanocidal activity of the compound was not related to its ability to produce a hypoglycemic state in the host, but the work with this compound led to investigation of a new series. **Dodecanediamidine,** $H_2N(NH{:})C(CH_2)_{10}C(:NH)NH_2$, was eventually prepared and shown to be superior to 1,1′-decamethylenediguanidine (33). A variety of spacing units was inserted between the two guanyl groups to develop the highly interesting series of diamidine compounds.

The most effective trypanocides of the diamidine types were found to be the isethionic acid ($HOCH_2CH_2SO_3H$) salts of **stilbamidine** (XI) (stilbamidine isethionate, N.N.R., 4,4′-stilbenedicarboxamidine di(2-hydroxyethanesulfonate)), **propamidine**

(XII), and **pentamidine** (XIII). All of these drugs are prepared in a similar way through the conversion of the requisite dinitriles to the imino ether hydrochlorides by the action of anhydrous hydrogen chloride on solutions of the dinitriles in ethyl alcohol, and thence to the diamidines by reaction of the intermediates with ammonia. The compounds have considerable and cumulative toxicity; therefore while (XI) and (XII) surpass (XIII) in activity, the lower toxicity of pentamidine isethionate has led to its wider use in the treatment of early cases of sleeping sickness. In particular, stilbamidine shows marked effects upon the nervous system, with the trigeminal nerve suffering the greatest damage. **2-Hydroxystilbamidine** (XI, R=OH) is considerably less toxic than (XI), but is more expensive and difficult to synthesize.



(XI) Stilbamidine (R = H)

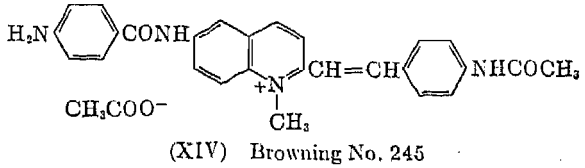


(XII) Propamidine ($n = 3$)
(XIII) Pentamidine ($n = 5$)

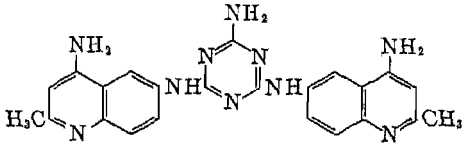
The combined use of pentamidine with suramin (X) tends to annul the toxic side effects of each with no apparent decrease in trypanocidal activity (24). A true salt **(4891RP)** of pentamidine with suramin, containing 45.5% of (X), 35.7% of (XIII), and 18.9% of water, has been made (78) and has been shown to have lower toxicity than either component with undiminished trypanocidal activity. It is currently undergoing experimental studies (63). The diamidine drugs have a wide range of pharmacologic and chemotherapeutic actions, and such matters have been discussed critically (65).

QUINOLINE, PHENANTHRIDINE, AND CINNOLINE DERIVATIVES

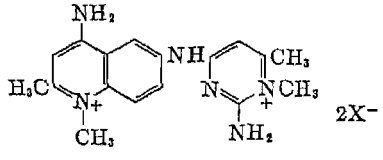
The *quinoline derivatives* which exhibit trypanocidal activity have usually been limited in use to veterinary practice. Investigations in this class seem to have been initiated by Browning, *et al.* in Britain (7). The best compound was **Browning No. 245** (XIV), but it failed to show satisfactory activity after careful evaluation. Another, more active trypanocidal quinoline derivative was prepared in Germany, and became known as **Surfen C** or Congasin (XV) (32). In Britain again a more satisfactory trypanocide, **Antrycide** (XVI), was synthesized by the group (12,75) responsible for the antimalarial drug proguanil. Antrycide is undergoing continuing field trials in the treatment of trypanosome infections in cattle.



(XIV) Browning No. 245

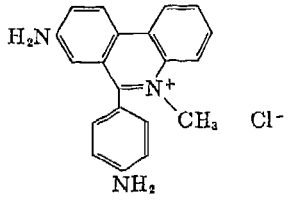


(XV) Surfen C

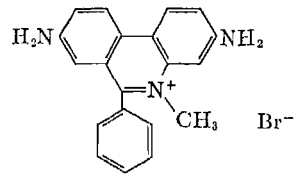


(XVI) Antrycide

All of the phenanthridine derivatives that show value in the treatment of the African trypanosomiases in cattle are quaternary salts (*phenanthridinium salts*). The first of this type to reach field trial was **Phenidium chloride** (XVII) (8,77), and then came **Dimidium bromide** (XVIII) (5,76). There is considerable improvement in trypanocidal activity when the quaternizing group in (XVIII) is a higher alkyl, for example, the ethyl group in Ethidium bromide, (71,74). Difficulties have been experienced in the use of certain phenanthridinium salts, because photosensitization develops in animals, including the hardy Zebu cattle.

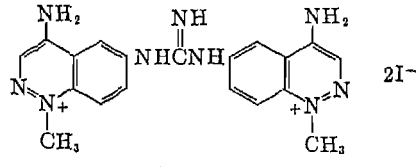


(XVII) Phenidium chloride



(XVIII) Dimidium bromide

A *cinnolinium salt* (**No. 528,** XIX) which has certain resemblances to the 4-aminoquinoline series has considerable activity in experimental trypanosomiasis (39,45). This field may prove to be of continuing interest in the development of new trypanocides.



(XIX)

Chemotherapy of Chagas' Disease

T. cruzi shows certain distinct and important differences in behavior when compared with the so-called African trypanosomes (see p. 331) and was at one time classified quite apart from them. Despite the advances that have been made in the treatment of the African trypanosomiases, no truly satisfactory drug is available for Chagas' disease, and much of the treatment is supportive in character, and essentially that employed in cases of congestive heart failure.

Interest in *T. cruzi* was increased because it was claimed (34,35) that the organism produced an endotoxin which had oncolytic effects. This has not been confirmed by most investigators (19,25,67). However, cultures of *T. cruzi* which have been pretreated at 48°C. may be used (47,56) in the cultivation of *Edamcba histolytica in vitro.* The latter organism, which is the causative agent of amebiasis, had not been obtained in bacteria-free cultures prior to this development; this may have considerable importance in the testing of amebacidal drugs.

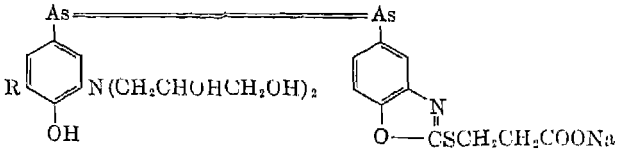
NATURAL PRODUCTS

The fact that Chagas' disease was not recognized as an entity until 1909 essentially precluded the development of folk remedies for this trypanosomiasis. The antibiotics, in general, fail to show appreciable activity against *T. cruzi* (49,58). *Quinine* has an unfavorable effect on infections by this parasite (10), as does cortisone (16).

ACTH (see Vol. **7**, p. 484) may have some beneficial action, but this has not been clearly established (57,58).

ARSENICALS

T. cruzi has shown remarkable refractoriness to the arsenicals which have definite activity against other trypanosomes. This has been a matter of considerable interest, especially in relation to the development of arsenic fastness in other species. Only two complex arsenobenzene derivatives have shown noteworthy activity against this parasite, namely **Bayer 9736 (As)** (XX) and **Bayer 10,557** (XXI) (26). Each of these

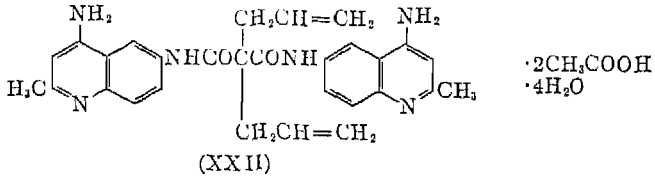


(XX) R = NHCOCH$_3$
(XXI) R = H

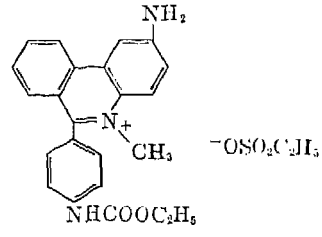
compounds has undergone limited clinical trial (14,36,51), the latter under the name Spirotrypan (26). The investigation of these types followed a pattern based on activity against arsenic-fast trypanosomes (26), and the final step lay in the reduction of the two arsonic acids to the mixed-type arsenobenzene in a single reaction mixture.

QUINOLINE DERIVATIVES

The first compound that showed activity in experimental Chagas' disease (which is best studied in juveniles, whether rodents or dogs) was a quinoline derivative, **Bayer 7602 (Ac)** (Chagavlon, XXII) (32). This drug is prepared by the reaction of 4,6-diaminoquinaldine with diallylmalonyl chloride. It has definite value in the clinic, especially in very early cases; however, its administration is very painful and its toxicity is considerable (36,42,51,58).



(XXII)



(XXIII) Carbidium sulfate

The *8-amino-6-methoxyquinolines*, which are well-known for potent antiplasmodial action (see Vol. **8**, p. 668), have been established also as valuable drugs in the treatment of *T. cruzi* infections (20,31,53,54,58). **Primaquine** (SN 13,272) seems to be the most effective of this group. Unfortunately, the 8-aminoquinolines show considerably

greater toxic side effects (as, for example, in the production of blood dyscrasias) among non-Caucasians, and Chagas' disease is more prevalent among the poorer groups, which have a heterogeneous ancestry in the Ibero-American areas where the spread of the parasite is most marked.

PHENANTHRIDINE TYPES

The discovery of antitrypanosomal activity among a series of phenanthridinium salts led to a broad, general program which eventually established the fact that certain derivatives which have urethan (*q.v.*) groupings were active against *T. cruzi* (7). A detailed evaluation of the structural variations and activity in the series (22) resulted in the choice of (XXIII) for further study; this compound was designated (21) 168C49 or **Carbidium sulfate.** The clinical use of this drug has been limited (44,51), but with results satisfactory enough to merit further trial.

Bibliography

(1) Ashley, J. N., Barber, H. J., Ewins, A. J., Newberry, G., and Self, A. D. H., *J. Chem. Soc.*, **1942**, 103.
(2) Baker, B. R., Joseph, J. R., and Williams, J. H., *Abstracts*, 126th Meeting, American Chemical Society, New York, 1954, p. 13N.
(3) Baker, B. R., Schaub, R. E., Joseph, J. R., and Williams, J. H., *J. Am. Chem. Soc.*, **76**, 4044 (1954).
(4) Banks, C. K., Gruhzit, O. M., Tillitson, E. W., and Controulis, J., *J. Am. Chem. Soc.*, **66**, 1771 (1946).
(5) Brown, A., *J. Trop. Med. Hyg.*, **16**, 167 (1913).
(6) Browning, C. H., Calver, R. M., and Adamson, H., *J. Pathol. Bacteriol.*, **60**, 336 (1948).
(7) Browning, C. H., Calver, K. M., Leckie, M. W., and Walls, L. P., *Nature*, **157**, 263 (1946).
(8) Browning, C. H., Cohen, J. B., Ellingsworth, S., and Gulbransen, R., *J. Pathol. Bacteriol.*, **29**, 317 (1926); *Proc. Roy. Soc. (London)*, **B105**, 99 (1929).
(9) Browning, C. H., Morgan, G. T., Robb, J. V. M., and Walls, L. P., *J. Pathol. Bacteriol.*, **46**, 203 (1948).
(10) Christen, R., Agosín, M., Jarpa, A., and Atias, A. V., *Bol. Inform. Parasit. Chilenas*, **6**, 23 (1951).
(11) Cosar, C., Ninet, L., Pennert-Sindico, S., and Preud'homme, J., *Compt. rend.*, **234**, 1498 (1952).
(12) Curd, F. H. S., and Davey, D. G., *Brit. J. Pharmacol.*, **5**, 25 (1950).
(13) Dortmann, H., *Z. Immunitätsforsch.*, **77**, 403 (1932).
(14) Elton, N. W., Personal communication, May 9, 1951.
(15) Fourneau, E., Trefouël, J., Trefouël, Mme. J., and Vallée, J., *Ann. inst. Pasteur*, **38**, 81 (1924).
(16) Fricbel, H., *Arch. exptl. Pathol. Pharmakol.*, **216**, 515 (1952).
(17) Friedheim, E. A. H., *J. Am. Chem. Soc.*, **66**, 1775 (1946).
(18) Friedheim, E. A. H., Vogel, H. J., and Berman, R. L., *J. Am. Chem. Soc.*, **69**, 560 (1947).
(19) Gailliard, H., Brumpt, L. C., and Martinez, R., *Bull. soc. pathol. exotique*, **43**, 204 (1950).
(20) Goble, F. C., *J. Parasitol.*, **35**, 375 (1949); *Antibiotics & Chemotherapy*, **2**, 265 (1952).
(21) Goodwin, L. G., Goss, M. D., and Lock, J. A., *Brit. J. Pharmacol.*, **5**, 287 (1950).
(22) Goodwin, L. G., Goss, M. D., Lock, J. A., and Walls, L. P., *Brit. J. Pharmacol.*, **5**, 277 (1950).
(23) Groot, H., Renjifo, S., and Uribe, C., *Am. J. Trop. Med.*, **31**, 673 (1951).
(24) Guimaraes, J. L., and Lourie, C. M., *Brit. J. Pharmacol.*, **6**, 514 (1951).
(25) Hauschka, T., Saxe, L. H., and Blair, M., *J. Natl. Cancer Inst.*, **7**, 189 (1947).
(26) Herrmann, W., and Hilmer, H., *Angew. Chem.*, **66**, 349 (1954).
(27) Hewitt, R. I., Wallace, W. S., Gumble, A. R., Gill, E. R., and Williams, J. H., *Am. J. Trop. Med. Hyg.*, **2**, 254 (1953).
(28) Heymann, B., *Z. angew. Chem.*, **37**, 585 (1924).
(29) Hutchings, B. L., Fryth, P. W., Waller, C. N., and Williams, J. H., *Abstracts*, 126th Meeting, American Chemical Society, New York, 1954, p. 13N.
(30) Janesó, N. von, and Janesó, H. von, *Z. Immunitätsforsch.*, **86**, 1 (1935).

(31) Jarpa, A., Christen, R., Agosín, M., Pizzi, T., and Cortes, R. J., *Bol. Inform. Parasit. Chilenas*, **5**, 19 (1950).
(32) Jensch, H., *Angew. Chem.*, **50**, 891 (1937).
(33) King, H., Lourie, E. M., and Yorke, W., *Ann. Trop. Med. Parasitol.*, **32**, 177 (1938).
(34) Klyueva, N. G., *Am. Rev. Soviet Med.*, **4**, 408 (1947).
(35) Klyueva, N. G., and Roskin, G., *Am. Rev. Soviet Med.*, **4**, 127 (1946).
(36) Laranja, F. S., Dias, E., and Nobrega, G., *Mem. inst. Oswaldo Cruz*, **46**, 473 (1948).
(37) Levaditi, C., and Twort, F. W., *Compt. rend. soc. biol.*, **70**, 645, 753 (1911); **71**, 127 (1911).
(38) Livingstone, D., *Brit. Med. J.*, **1858**, I, 360.
(39) Lourie, E. M., Morley, J. S., Simpson, J. C. E., and Walker, J. M., *Brit. J. Pharmacol.*, **6**, 643 (1951).
(40) Lourie, E. M., and Yorke, W., *Ann. Trop. Med. Parasitol.*, **31**, 435 (1937).
(41) Lourie, E. M., and Yorke, W., *Ann. Trop. Med. Parasitol.*, **33**, 289 (1939).
(42) Mazza, S., *Deut. Tropenmed. Z.*, **45**, 577 (1941).
(43) McCowen, M. C., Callender, M. E., Lawlis, J. F., and Brandt, M. C., *Am. J. Trop. Med. Hyg.*, **2**, 212 (1953).
(44) Monteiro de Barros, O., and Pupo Noguiera, D., *Rev. Clin. São Paulo*, **27**, 79 (1951).
(45) Morley, J. S., and Simpson, J. C. E., *J. Chem. Soc.*, **1952**, 2617.
(46) Mulligan, H. W., Personal communication, Nov. 18, 1952.
(47) Nakamura, M., and Anderson, H. H., *Exptl. Parasitol.*, **1**, 66 (1951).
(48) Neghme, A., *Science*, **101**, 115 (1945).
(49) Packchanian, A., *Am. J. Trop. Med. Hyg.*, **2**, 243 (1953).
(50) Pearce, L., and Brown, W. H., *J. Exptl. Med.*, **28**, 109 (1918).
(51) Pellegrino, J., and Lobo de Rezende, C., *Mem. inst. Oswaldo Cruz*, **51**, 545 (1953).
(52) Phillips, B. P., *Science*, **111**, 8 (1950); *Am. J. Trop. Med.*, **31**, 290 (1951); *Am. J. Trop. Med. Hyg.*, **2**, 47 (1953).
(53) Pizzi, T., *Proc. Soc. Exptl. Biol. Med.*, **78**, 643 (1951).
(54) Pizzi, T., Rubio, M., and Knierim, F., *Bol. Chileno de Parasitol.*, **9**, 35 (1954).
(55) Porter, J. N., Hewitt, R. I., Hesseltine, C. W., Kruppa, G., Lowery, J. A., Wallace, W. S., Bohonis, N., and Williams, J. H., *Antibiotics & Chemotherapy*, **2**, 409 (1952).
(56) Robles Gil, J., and Perrín, M., *Arch. inst. cardiol. Méx.*, **20**, 314 (1950).
(57) Rodrigues Philocreon, D., *Arquiv. univ. Bahia, Fac. med.*, **6**, 107 (1951).
(58) Romaña, C., *Anales Inst. Med. Regional*, **3**, 255 (1953).
(59) Rubin, B. A., *J. Bacteriol.*, **53**, 375 (1947).
(60) Seneca, H., and Ides, D., *Antibiotics & Chemotherapy*, **3**, 117 (1953).
(61) Schatz, A., Magnuson, H. J., Waksman, S. A., and Eagle, H., *Proc. Soc. Exptl. Biol. Med.*, **62**, 143 (1946).
(62) Schilling, C., *Arch. Schiffs- u. Tropen-Hyg.*, **23**, 317 (1919).
(63) Schneider, J., and Montezin, G., *Bull. soc. pathol. exotique*, **47**, 249 (1954).
(64) Schnitzer, R. J., *Ann. N. Y. Acad. Sci.*, **55**, Art. 6, 1090 (1952).
(65) Schoenbach, E. G., and Greenspan, E. M., *Medicine*, **27**, 327 (1948).
(66) Schweitzer, A., Personal communication, Sept. 19, 1952.
(67) Spain, D. M., Molomut, N., and Warshaw, L. J., *Proc. Soc. Exptl. Biol. Med.*, **69**, 134 (1948).
(68) Takeyama, S., *Fukuoka Ikwadaigaku Zasshi*, **19**, No. 10 (1927).
(69) Tobie, E. J., *Am. J. Trop. Med. Hyg.*, **3**, 852 (1954).
(70) Waller, C. N., Fryth, P. W., Hutchings, B. L., and Williams, J. H., *J. Am. Chem. Soc.*, **75**, 2025 (1953).
(71) Watkins, T. I., *J. Chem. Soc.*, **1952**, 3059.
(72) Weinman, D., *Proc. Soc. Exptl. Biol. Med.*, **54**, 38 (1943).
(73) Wolf, A., Kabat, E. A., Bezer, A. E., and Fonseca, J. R., *Federation Proc.*, **10**, 375 (1951).
(74) Woolfe, G., *Ann. Trop. Med. Parasitol.*, **46**, 285 (1952).
(75) British Pat. 658,205 (Oct. 26, 1949), F. H. S. Curd, G. J. Stacey, H. W. Thompson, and C. H. Vasey (to Imperial Chemical Industries, Ltd.).
(76) British Pat. 587,673 (Jan. 3, 1944), L. P. Walls.
(77) British Pat. 679,128 (Nov. 23, 1950), L. P. Walls and N. Whittaker (to Wellcome Foundation, Ltd.).
(78) French Pat. 1,050,956 (Feb. 20, 1952), P. Galliot (to Société des Usines Chimiques Rhône-Poulenc).

(79) U.S. Pat. 2,430,462 (May 19, 1944), E. A. H. Friedheim.
(80) U.S. Pat. 2,659,723 (Jan. 28, 1947), E. A. H. Friedheim.

GENERAL REFERENCES

(81) Banks, C. K., "Chemotherapy," in Powers, ed., *Advancing Fronts in Chemistry*, Vol. II, Reinhold, N.Y., 1946, p. 71.
(82) Brand, E. von, *The Chemical Physiology of Endoparasitic Animals*, Academic Press, N.Y., 1952.
(83) Brumpt, E., *Précis de Parasitologie* (6ème. édition), Masson et Cie., Paris, 1949, pp. 277–346.
(84) Burger, A., *Medicinal Chemistry*, Vol. II, Interscience, N.Y., 1951, p. 842.
(85) Findlay, G. M., *Recent Advances in Chemotherapy*, Vol. I, Churchill, London, 1950, p. 359.
(86) Fischl, V., and Schlossberger, H., *Handbuch der Chemotherapie*, Vol. II, Fischers, Leipzig, 1934.
(87) Gradwohl, R. B. H., Benitez Soto, L., and Felsenfeld, O., eds., *Clinical Tropical Medicine*, Mosby, St. Louis, 1951, pp. 127, 156.
(88) Harley, G. W., *Native African Medicine*, Harvard University Press, Cambridge, Mass., 1941.
(89) Hoare, C. A., *Proceedings of Fourth International Congresses on Tropical Medicine and Malaria* (Washington, D.C., May 10–18, 1948). U.S. Department of State, Washington, D.C., 1948, Vol. II, p. 1110.
(90) Hoare, C. A., *Handbook of Medical Protozoology*, Baillière, Tindall and Cox, London, 1949, pp. 170–217.
(91) Ing, H. R., in Gilman, ed., *Organic Chemistry, an Advanced Treatise*, Vol. III, Wiley, N.Y., 1953, p. 500.
(92) Lwoff, M., in Lwoff, ed., *Protozoa*, Vol. I, Academic Press, N.Y., 1951, pp. 128–146.
(93) Richardson, U. F., *Veterinary Protozoology*, Siver and Boyd, London, 1948, pp. 92–144.
(94) Wagner-Jauregg, T., *Therapeutische Chemie*, Hans Huber, Bern, 1949, p. 168.

E. A. STECK

TRYPARSAMIDE, $NaHO_3AsC_6H_4NHCH_2CONH_2$. See *Arsenic preparations*, Vol. **2**, p. 129; *Trypanocides*, Vol. **14**, p. 332.

TRYPSIN. See *Enzymes*, Vol. **5**, pp. 752, 758, 759.

TRYPTOPHAN, TRYPTOPHANE, $C_6H_4.NH.CH:CCH_2CH(NH_2)COOH$. See *Amino acids*, Vol. **1**, pp. 719, 720, 726; *Indole*, Vol. **7**, p. 843.

TUBERCULOSTATIC AGENTS

Tuberculostatic agents are compounds that have proved active against strains of *Mycobacterium tuberculosis* (*Bacillus tuberculosis*), which are the causative agents of the infectious disease tuberculosis and were first isolated by Koch in 1882. Although thousands of compounds of natural and synthetic origin have been tested and found active at low concentrations in inhibiting the growth of these bacteria *in vitro*, the number giving a positive chemotherapeutic response in well-controlled animal tests is in the low hundreds and the number showing demonstrated clinical usefulness may be counted on the fingers of one hand. Nevertheless, the clinician by appropriate use of combinations of these drugs together with bed rest and surgery where indicated has made marked strides in the control of the disease even in advanced cases and hitherto uniformly fatal forms.

Tuberculosis has been known as phthisis since the time of Hippocrates; it was also called "consumption" much later. It may affect any organ or tissue in the body but the most common form is tuberculosis of the lung, which causes more than 90% of the deaths due to tuberculosis in the U.S. and more than 80% of such deaths in Great Britain. The disease may vary in intensity from the "latent tuberculosis" which shows no change over a prolonged period of time, but is incompletely

healed and potentially active, to the acute generalized tuberculosis (acute miliary or disseminated tuberculosis), in which the bacteria are widely distributed in large numbers throughout the body, and which, without treatment, is rapidly fatal.

The *M. tuberculosis* are "acid-fast" bacteria which exist in numerous varieties of different virulence. The most important pathogenic varieties are the human, the bovine, and the avian, although the avian variety is rarely the causative agent of the disease in man. The strains are distinguished usually by their cultural characteristics and by their ability to infect various experimental animals. However, there are many strains which occupy an intermediate position in their growth characteristics and their pathogenicity for animals and cannot be classified definitely as either the human or the bovine type.

The bacteria may gain entrance to the body by inhalation, ingestion, or directly through the skin, inhalation being the most usual route. The tubercle bacilli multiply unchecked when first introduced, with the infecting organisms held temporarily and mechanically in the regional lymph nodes, but in a period of days they reach the thoracic ducts and the general circulation. Since all the venous blood passes through the capillary bed of the lungs before redistribution throughout the body, the lung tissue presents the first filter to be encountered by the blood-borne bacilli. Thus the inflammation and ulcerative processes are set up in the lung tissue. The primary lesion develops in the lungs, and the tracheo-bronchial lymph nodes are infected most intensively. Some of the bacilli may remain in other tissues in microscopic foci that can give rise years later to infection of bones, joints, or the various organs of the body.

Screening

The most rapid method of screening compounds as possible tuberculostatic agents is the *in vitro* test in which one of the many strains of *M. tuberculosis* is grown under carefully controlled conditions, and the limiting concentration of the compound that inhibits growth is determined. With such a procedure, literally thousands of compounds have been checked, a large number of which have shown a pronounced inhibitory action on the growth of the test organism at low concentrations. However, further study of these active compounds showed that there was a poor correlation between *in vitro* activity and chemotherapeutic efficiency (17,55), and many investigators have indicated that the *in vitro* test was of little value (10,24). However, with the exception of nicotinamide and pyrazinecarboxamide, all compounds having clinical use have shown *in vitro* activity. (In certain series, derivatives of active compounds have been synthesized in which *in vitro* activity is lost, but metabolic studies indicate that these inactive derivatives are metabolized *in vivo* to the active component.) Modifications of the simple *in vitro* test have been attempted to obtain a better correlation with *in vivo* tests. A combined *in vitro-in vivo* test was developed in which the compound is given to test animals either intraperitoneally (8) or orally (87), and the citrated blood used to determine *in vitro* activity. This test thus takes into consideration the effect of metabolic processes, poor absorption, rapid excretion, and toxicity.

Various *in vivo* tests have been developed for the testing of compounds as tuberculostatic agents. These include the chick embryo test (22,46), the rabbit cornea test (31), the mouse cornea test (69) and various animal tests in which the infected host may be chicks (80), rabbits (49), guinea pigs (43), mice (1,53,68), or hamsters (18). The most useful of these seems to be the *in vivo* test in mice or guinea pigs. The mouse test permits a large number of compounds to be tested in a relatively short time. The choice of the mouse strain, the choice of the strain of *M. tuberculosis*, the size of the inoculum, and the route of inoculation are all of importance and must be carefully standardized to obtain significant results (21,51,66). The efficacy of a compound is usually determined by the increase in survival time of the mice, although

other factors such as loss or gain in weight of the mice and the nature and distribution of the infection in the animals are also of significance. The guinea pig test suffers from the disadvantage that more space, more drug, and much more time are needed to test a compound. However, since treatment may be delayed in the test until the disease is well established, the value of a drug for its curative properties may be more readily determined. Monkeys have also been used as test animals since it is claimed that tuberculosis in monkeys resembles human tuberculosis very closely (29).

All tuberculostatic agents that have been studied to any extent, cause the emergence of strains resistant to the agent used. Therefore these drugs are generally used in combination, since such combinations have been shown to increase the time before resistant strains develop. The development of resistant strains depends to a significant degree on the dosage regime used. Cross resistance is shown only between members of a given series and does not seem to occur between members of different series.

The final test for the compound is the clinical trial. In a chronic disease such as tuberculosis the evaluation of drugs is especially difficult since many factors are involved, and only studies on large numbers of patients over long periods of time are meaningful. In tuberculosis especially, where the development of resistance to drugs occurs and where the physical condition of the patient alters the course of the disease so markedly, the clinical comparison of active compounds is very difficult. Clinical activity of a therapeutic agent in pulmonary tuberculosis may manifest itself in several ways such as decrease in fever, decrease in sputum volume and living bacteria, increase in appetite and gain in weight, x-ray improvement, and finally an apparent increase in survival time of the patients.

Natural Products

ANTIBIOTICS

Many antibiotics (*q.v.*), especially many of those produced by various actinomycetes (see *Streptomyces antibiotics*; *Tetracyclines*), have given evidence of their value as tuberculostatics.

The isolation of streptomycin and its subsequent use in the treatment of human tuberculosis marked the introduction of the first important agent for the chemotherapy of tuberculosis. **Streptomycin,** U.S.P. XIV, N.N.R., is produced by *Streptomyces griseus*. Its structure is made up of three moieties, streptidine, streptose, and *N*-methyl-L-glucosamine (see Vol. **13,** p. 67) joined to one another by glycosidic linkages. The compound shows high *in vitro* activity and *in vivo* activity in experimental animals if given by injection; but shows little activity when given orally because of its very poor absorption. Clinically, the compound has been an effective agent for treatment of the various forms of tuberculosis (85).

From the fermentation broths of various streptomycin-producing actinomycetes there has also been isolated a related compound, **mannosidostreptomycin.** It differs from streptomycin itself in having an additional mannose residue, which is joined by a $1 \rightarrow 4$ linkage to the *N*-methyl-L-glucosamine moiety of streptomycin. This compound apparently is somewhat less active than streptomycin (67).

The reduction of the aldehyde group in streptomycin to a primary alcohol produces **dihydrostreptomycin,** N.N.R., which shows similar activity to streptomycin in experimental animals and in clinical trials. However, there is one remarkable differ-

ence between streptomycin and dihydrostreptomycin. Upon prolonged use at high dosage levels, streptomycin may cause vestibular damage, while the use of dihydrostreptomycin may result in some loss of hearing (cochlear damage). A mixture of equal parts of streptomycin and dihydrostreptomycin has been introduced recently. This mixture retains the antituberculous activity of each component, since the action is additive, but greatly reduces the toxicity by diminishing the dose of each toxic component (36).

Other derivatives of streptomycin have been prepared in which the aldehyde function of the molecule has been condensed with amines. These compounds retain some of the antibacterial activity of streptomycin but have increased toxicity and are not useful clinically. Various degradation products of streptomycin (see Vol. **13,** p. 69) have also been screened for antituberculous activity, but none of these compounds shows appreciable activity, even *in vitro.*

Viomycin is produced by *Streptomyces vinaceus* and other species of *Streptomyces* (see Vol. **13,** p. 108). It has shown activity *in vitro* and in experimental animals, although it is less active than streptomycin. Its clinical activity has also been demonstrated, but in these clinical tests the toxicity of the compound greatly limited its usefulness. Because it is more toxic than streptomycin, it should be used only in those cases that do not respond to streptomycin or other chemotherapy, and then only under careful observation (77).

Oxytetracycline, N.N.R. (Terramycin), produced by *Streptomyces rimosus,* is a naphthacene derivative (81) (see Vol. **13,** p. 790). It has a bacteriostatic effect upon *M. tuberculosis in vitro* and *in vivo* (25). The drug had very little therapeutic effect in clinical trials when used as the sole agent. It is reported, however, to be effective when used in combination with streptomycin in delaying the emergence of strains resistant to streptomycin (74).

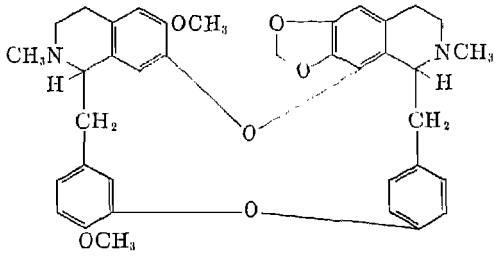
The related antibiotics **tetracycline** (Tetracyn, Achromycin) and **chlortetracycline** (Aureomycin, U.S.P. XIV, N.N.R.) (61,65) have shown *in vitro* activity, but chlortetracycline has not exhibited *in vivo* activity in mice or in guinea pigs (possibly due to lack of stability). Tetracycline would be expected to show *in vivo* activity similar to that of oxytetracycline because of their close structural similarity. See also *Tetracyclines.*

Neomycin, N.N.R., isolated from the fermentation of *Streptomyces fradiae,* has shown *in vitro* activity and *in vivo* activity in both mice (64) and guinea pigs (41). Although clinical studies indicate that it may have some activity, the toxic reactions of neomycin are such as to render this drug of little or no clinical value in the treatment of tuberculosis (12). See also Vol. **13,** p. 90.

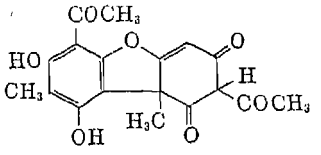
Other antibiotics such as *mycomycin* and *erythromycin,* N.N.R. (see Vol. **13,** pp. 59, 94), have been screened for possible activity against tuberculosis in view of their high *in vitro* activity. However, neither of these has shown any clinical value (40,73).

MISCELLANEOUS NATURAL PRODUCTS

Many other products isolated from natural sources have been tried as agents for the treatment of tuberculosis. Perhaps the one compound most extensively studied is the alkaloid **cepharanthine**(I), isolated from *Stephania cepharantha* or *S. sasakii.* It has been reported to be active in the treatment of tuberculosis in Japan, but attempts to show *in vitro* or *in vivo* activity in experimental animals have been unsuccessful, throwing some doubt as to its actual clinical efficacy. Other products such as **diploi-**

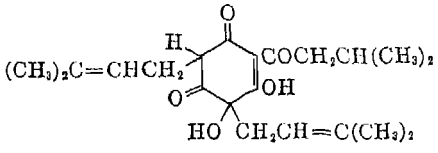


(I) Cepharanthine

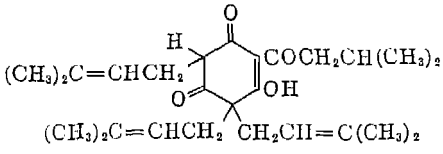


(II) Usnic acid

cin, isolated from the lichen *Buellia canescens* and having a tricyclic diphenyl ether–lactone structure, have been reported to inhibit *M. tuberculosis in vitro*, but were found to be inactive in guinea pigs and have not been tried clinically (2). **Usnic acid** (usninic acid), derived from the lichen *Pamalina reticulata*, has also shown *in vitro* activity, but *in vivo* tests have been negative (52). Several structures have been proposed for usnic acid, only one of which (II) is shown here. Finally, there have been



(III) Humulone



(IV) Lupulone

reports that the compounds **humulone**(III) and **lupulone**(IV), isolated from hops, have *in vitro* and *in vivo* activity (14). The activity, if present, is of such a low order that further testing has not been warranted.

Synthetic Tuberculostatic Agents

p-AMINOSALICYLIC ACID

The search among compounds related to benzoic acid as possible antibacterial agents led to the discovery of the tuberculostatic activity (47) of *p*-aminosalicylic acid, N.N.R., (PAS), $NH_2C_6H_3(OH)COOH$ (see Vol. **12,** p. 57), m.p. 135–140°C. (decompn.). It shows good *in vitro* activity and only low but definite *in vivo* activity. It has a definite clinical effect, but because of its low activity very large doses of the compound are required. The resulting toxicity makes its use as an independent agent for the treatment of tuberculosis impractical. However, clinical tests show that it is very effective in combination with other therapeutic agents, since it greatly delays the development of strains resistant to the more active agents such as streptomycin or isoniazid.

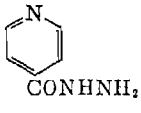
Numerous derivatives of *p*-aminosalicylic acid have been prepared in an attempt to obtain more active compounds. One of these, the *phenyl ester* (30), has been reported to be effective *in vivo* especially if injected in oil solution, but confirmation of these results has not been obtained. No clinical trial of this compound has been reported. A novel formulation, in which the *p*-aminosalicylic acid is adsorbed on a resin, has been tried and is reported to be much better tolerated than the acid itself.

HYDRAZIDES

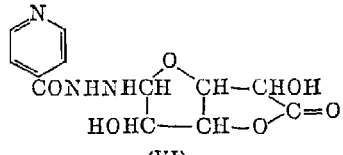
The most active of the synthetic tuberculostatic agents is isonicotinic acid hydrazide (INH) (see Vol. **11,** p. 291), **isoniazid,** N.N.R.(V) (7,33,58), m.p. 170–173°C.

It is very soluble in water and only sparingly so in alcohol. Isoniazid is prepared by the reaction of methyl isonicotinate with hydrazine. It shows high *in vitro* activity and is active in both the mouse (7,33) and the guinea pig (42) *in vivo* tests. Clinical trials show it to be a very effective antitubercular agent in the various types of tuberculosis (71), especially tuberculous meningitis and miliary tuberculosis (15). Although isoniazid, like other tuberculostatic agents, gives rise to resistant strains of tubercle bacilli, the significance of such strains is questioned. These strains appear to be less virulent than nonresistant strains, and, in fact, various investigators have been unable to use these resistant strains in their experimental mouse studies since they are unable to kill the mice with the resistant strain.

Since the first reports of its activity, literally hundreds of derivatives of isoniazid have been prepared (28,59,89). From the *in vitro* and *in vivo* testing of these derivatives certain generalizations concerning the relationship of structure to activity in this series can be made (5). The introduction of a substituent in the pyridine ring or the reduction of the pyridine ring causes loss of *in vitro* and *in vivo* activity. Alkylation or acylation of the hydrazine nitrogen (the 2-position) produces derivatives which are active *in vivo* but have low *in vitro* activity. Condensation of isoniazid with aldehydes or ketones, including sugars, yields derivatives which are active both *in vitro* and *in vivo*.

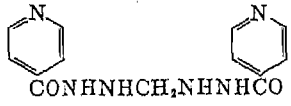


(V) Isoniazid

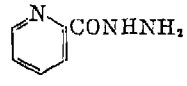


(VI)

Although none of the derivatives of isoniazid is more active than the parent compound in experimental animals, the apparent higher therapeutic ratio (fraction of the minimum lethal dose that is effective) in these animals has led to more complete testing clinically. The derivatives studied include the 2(or *N'*)-isopropyl derivative, C_5H_4N-$CONHNHCH(CH_3)_2$ (33), and the glucuronide and galacturonide of isonicotinic acid hydrazide (VI) (75,76). The *isopropyl derivative* (33) shows clinical activity, but its therapeutic ratio is lower than that of isoniazid, and its use in the treatment of tuberculosis does not appear promising. The *glucuronide* (75,76) also shows good clinical activity and low toxicity. However, in this case, the effective dose is much higher than that of isoniazid and recent studies have indicated that it is active only as a result of breakdown to the parent hydrazide. Other hydrazide derivatives such as the *formaldehyde derivative* (VII), the *sodium salt of the 2-sulfomethyl derivative*, $C_5H_4NCONHNHCH_2SO_3Na$, and the *2-p-hydroxybenzyl derivative*, $C_5H_4NCONHNH$-$CH_2C_6H_4OH$, (78), have all been reported to have the advantages, from a pharmaceutical point of view, of longer duration of action and slower absorption or slower excretion. However, there is little clinical evidence to support these claims. An interesting pharmaceutical form of isoniazid is the *hydrazone formed with streptomycin* (5). This compound contains the two therapeutically active components in approximately the recommended dose ratio.



(VII)



(VIII) Picolinic acid hydrazide

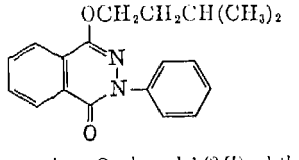
Activity in the hydrazide series is not limited to isonicotinic acid hydrazide and its derivatives. **Picolinic acid hydrazide** (VIII) (7), **2-furoic acid hydrazide** (IX) (6), **2-thiophenecarboxylic acid hydrazide** (X) (6), and **2-thiazolecarboxylic acid hydrazide** (XI) (88) have all been reported to have *in vitro* and *in vivo* activity. Even benzoic acid hydrazide itself has been reported to be active against certain strains of *M. tuberculosis*. In this series there is a marked strain specificity, since furoic acid hydrazide, although reported active in an *in vivo* test in which the infecting agent was a Ravenel strain, has been reported to be inactive if the infecting agent was the $H_{37}Rv$ strain (88).

(IX) 2-Furoic acid hydrazide

(X) 2-Thiophenecarboxylic acid hydrazide

(XI) 2-Thiazolecarboxylic acid hydrazide

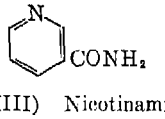
Structurally related to these acyl hydrazides are the bicyclic **phthalazines** (phthalylhydrazines). Among the most active of these is *1-isoamyloxy-3-phenyl-4-keto-3,4-dihydrophthalazine* (4-isoamyloxy-2-phenyl-1(2*H*)-phthalazinone) (XII), one of a series containing various alkoxy substituents, which is active *in vitro* and *in vivo* (11). However, because of the high toxicity of these compounds, clinical trials have not been carried out.



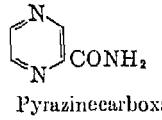
(XII) 4-Isoamyloxy-2-phenyl-1(2*H*)-phthalazinone

AMIDES

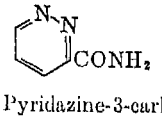
The one series of compounds which do not show *in vitro* activity but do show *in vivo* activity is the heterocyclic amide group consisting of **nicotinamide** (XIII) (13), U.S.P. XIV, N.N.R., m.p. 131–132°C. (see Vol. **9**, p. 305), **pyrazinecarboxamide** (XIV) (45), and **pyridazine-3-carboxamide** (XV) (72). The activity appears to be specific since modification of the molecules, either by ring substitution or by substitution on the amide nitrogen, causes decrease or loss of activity (44). Nicotinamide and pyridazine-3-carboxamide show *in vivo* activity only at high levels, and clinical trials with nicotinamide do not appear promising because of the toxic effects produced by levels required for tuberculostatic action. However, pyrazinecarboxamide has



(XIII) Nicotinamide



(XIV) Pyrazinecarboxamide



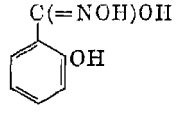
(XV) Pyridazine-3-carboxamide

shown good clinical results for short periods of time (90). Strains of bacteria resistant to the compound develop quite rapidly, and its usefulness as a chemotherapeutic agent will depend on the ability of other drugs, when given along with it, in preventing or delaying this development of resistant strains. A recent study has shown that a combination of pyrazinecarboxamide and isoniazid has special tuberculocidal proper-

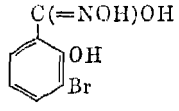
ties. However, the toxicity of the mixture at the levels required for this effect prevents its general use (50).

HYDROXAMIC ACIDS

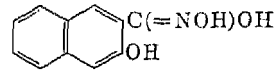
Another series of aromatic acid derivatives for which antitubercular activity has been reported is the *o*-hydroxy aromatic hydroxamic acids. The compounds of this type for which activity has been claimed include **salicylohydroxamic acid** (XVI), **3-bromosalicylohydroxamic acid** (XVII), and **3-hydroxy-2-naphthohydroxamic acid** (XVIII). These compounds were reported to be active *in vitro* and *in vivo* and also to be clinically effective (83,84).



(XVI) Salicylohydroxamic acid



(XVII) 3-Bromosalicylohydroxamic acid



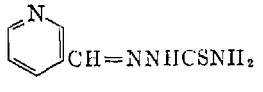
(XVIII) 3-Hydroxy-2-naphthohydroxamic acid

THIOSEMICARBAZONES

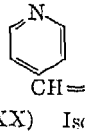
A series of compounds showing high antituberculous activity in experimental animals are the thiosemicarbazones of aromatic aldehydes (20). These compounds show high *in vitro* and *in vivo* activity. A thorough documentation of the relation of structure to activity in the series has been made (4,34,38).

Several of the more promising compounds, such as **p-acetamidobenzaldehyde thiosemicarbazone** (tibione), $CH_3CONHC_6H_4CH{=}NNHCSNH_2$, and ***p*-ethylsulfonylbenzaldehyde thiosemicarbazone,** $C_2H_5SO_2C_6H_4CH{=}NNHCSNH_2$, have had clinical trials, and although promising results were obtained in many cases (19,56), the toxicity of the series apparently precludes their use in chronic cases of tuberculosis.

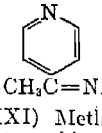
The active compounds in the aromatic series are limited in general to the para-substituted benzaldehyde thiosemicarbazones. However, it has been observed that both **nicotinaldehyde thiosemicarbazone** (XIX) (48) and **isonicotinaldehyde thiosemicarbazone** (XX) (27) show activity in experimental animals, and in the case of (XIX) clinical activity has also been reported.



(XIX) Nicotinaldehyde thiosemicarbazone

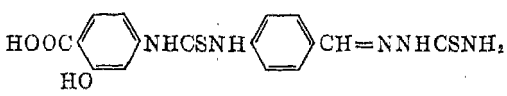


(XX) Isonicotinaldehyde thiosemicarbazone



(XXI) Methyl 4-pyridyl ketone thiosemicarbazone

In addition to these thiosemicarbazones of aldehydes, it is interesting to note that **methyl 4-pyridyl ketone thiosemicarbazone** (XXI), a derivative of 4-acetylpyridine, has also shown good *in vitro* and *in vivo* activity (27,32). A combination (XXII) of the thiosemicarbazone type and *p*-aminosalicylic acid has also been synthesized, which has good *in vitro* and *in vivo* activity, as would be expected from a para-substituted



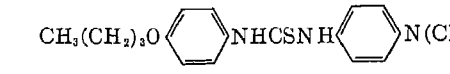
(XXII)

benzaldehyde (35). However, it is no more active nor appreciably less toxic than other thiosemicarbazones, and clinical studies have not been reported.

THIOUREAS

Another series of compounds recently reported to have both *in vitro* and *in vivo* activity are the substituted thiocarbanilides (39,54), two of the more interesting members being **4-ethoxy-4′-isobutoxythiocarbanilide** (XXIII) and **4-butoxy-4′-dimethylaminothiocarbanilide** (XXIV). Studies on correlation of structure to activity in

(XXIII) 4-Ethoxy-4′-isobutoxythiocarbanilide

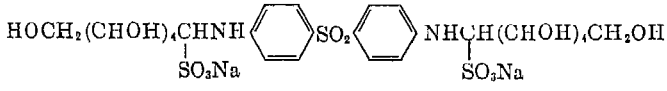


(XXIV) 4-Butoxy-4′-dimethylaminothiocarbanilide

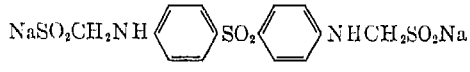
this series show a maximum activity when the alkoxy groups are propoxy or butoxy. Replacement of an alkoxy group by an alkyl group of equal length results in similar activity. One of the alkoxy groups may be replaced by halogen or dialkylamino and the molecule still retains activity. However, replacement of both alkoxy groups by amino groups or halogens causes loss of activity. Only substitution in the para position of the phenyl rings results in activity (39). Compounds (XXIII) and (XXIV) are under clinical investigation, and preliminary reports indicate that they are therapeutically effective (62).

SULFONES AND SULFONAMIDES

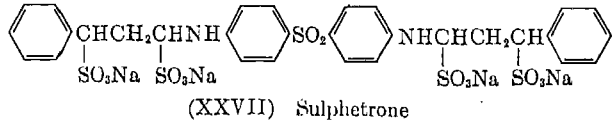
The first group of compounds reported to be active in experimental tuberculosis, although this activity was only minimal, were the sulfones of which ***p,p′*-diaminodiphenyl sulfone** (4,4′-sulfonyldianiline, bis(*p*-aminophenyl) sulfone, DDS), $NH_2C_6H_4SO_2C_6H_4NH_2$, m.p. 108°C., is the parent type (70). This compound is active *in vitro* and *in vivo* and has been shown to have some clinical efficacy. However, its high toxicity made it evident that it could not be used generally. Numerous derivatives of *p,p′*-diaminodiphenyl sulfone were prepared such as *Promin* (XXV) (26), *sulfoxone sodium*, N.N.R. (Diasone Sodium) (XXVI) (63), and *Sulphetrone* (XXVII) (9). See also Vol. **13**, p. 344.



(XXV) Promin



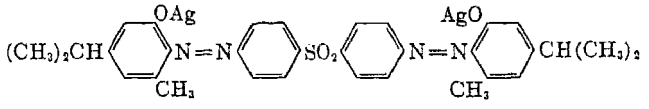
(XXVI) Sulfoxone sodium



(XXVII) Sulphetrone

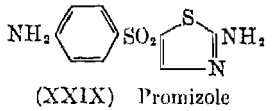
These compounds, which are active clinically, have reduced toxicity as compared to *p,p′*-diaminodiphenyl sulfone, but high doses of the agents are needed. These derivatives were shown to be active only in so far as they are degraded to the parent sulfone (82), and their use as antitubercular agents has not been very successful.

Many modifications of the diaminodiphenyl sulfone molecule have been made, but apparently only the alkylated amino derivatives show activity, and at the present time only one of these, *p-amino-p'-(hydroxyethyl)aminodiphenyl sulfone* (2-(*p*-sulfanilylanilino)ethanol), $NH_2C_6H_4SO_2C_6H_4NHCH_2CH_2OH$, appears of interest. This compound is active *in vitro*, *in vivo* (79), and appears to have some activity in clinical trials. However, this activity is low, and the compound has been recommended only for use in combined therapy with other active agents such as streptomycin, since clinical trials indicate that it delays the development of strains resistant to streptomycin (60). An interesting modification of the diaminodiphenyl sulfone molecule, the *disilver derivative of 6,6'-[sulfonylbis(p-phenyleneazo)]di-5-m-cymenol* (the silver salt of 4,4'-bis(azo-*p*-isopropyl-*m*-cresol)diphenyl sulfone) (XXVIII), is claimed to be effective clinically (86).



(XXVIII)

In addition to these modifications of the molecule, the replacement of one or both of the benzene rings has been carried out. Using this synthetic approach, the compound *Promizole* (XXIX) was prepared and is considered by some to be the best of the sulfones (25).

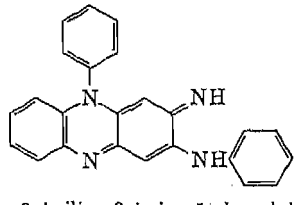


(XXIX) Promizole

The introduction of the various sulfonamides (*q.v.*; see also *Sulfa drugs*) in bacterial chemotherapy led to the trial of various compounds of this type as antitubercular agents (57). The sulfonamides, in general, show *in vitro* activity of a low order and minimal *in vivo* activity. None of them, however, has been of clinical value in the treatment of tuberculosis.

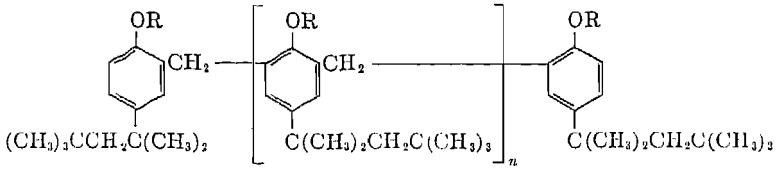
MISCELLANEOUS SYNTHETIC AGENTS

Simulation of the structural features of diploicin (see p. 344) resulted in the preparation of a number of substituted diphenyl ethers and diphenylamine types. During the *in vitro* testing of *o*-aminodiphenylamine, the formation of **2-anilino-3-imino-5-phenylphenazine** (XXX) was observed. This compound shows high *in vitro* and *in vivo* activity, and clinical trial has indicated that it has some suppressive effect in renal tuberculosis (2). A number of related compounds have also been prepared which also show *in vitro* activity.



(XXX) 2-Anilino-3-imino-5-phenylphenazine

The surface-active agent *Triton A-20*, a nonionic arylalkyl polyether of phenol, has been reported to have a suppressive action on tuberculosis in mice (16), but it is too toxic to be of further interest. However, the observation of its activity stimulated the synthesis of similar compounds of the general type of (XXXI). These compounds are less toxic than Triton A-20 and approach its activity when n is 2 to 6 (16).



(XXXI) (R = $[-CH_2CH_2O]_7CH_2CH_2OH$)

Another compound showing *in vivo* activity is **ethyl 3-methyl-2-*n*-dodecylsuccinate,** $C_2H_5OOCCH(CH_3)CH(C_{12}H_{25})COOH$, which has been reported to have some clinical use in the local treatment of tuberculous infections, but is of little or no value in systemic infections (2,3).

A series of **pyridine compounds** related to 5-amino-2-butoxypyridine, $CH_3(CH_2)_3O(C_5H_3N)NH_2$, has also been prepared and is reported to be active *in vitro* and *in vivo* (23). Clinical studies have shown these compounds to be too toxic for use as chemotherapeutic agents.

A number of compounds related to products isolated from the tubercle bacilli have also been screened for activity. Various **quinones** (*q.v.*), including 2-hydroxy-3-methylnaphthoquinone (phthiocol) structurally related to the vitamin K's, which has been shown to be present in the organism, and various **long-chain fatty acids** have been tested and show *in vitro* activity but no *in vivo* activity.

Bibliography

(1) Baker, M. J., Schlosser, M. E., and White, H. J., *Ann. N.Y. Acad. Sci.*, **52**, 678 (1949).
(2) Barry, V. C., *Proc. Colloq. Chemotherapy Tubere.*, **1951**, 47.
(3) Barry, V. C., Belton, J. G., Conalty, M. L., and Twomey, D., *Nature*, **166**, 303 (1950).
(4) Behnisch, R., Mietzsch, F., and Schmidt, H., *Am. Rev. Tuberc.*, **61**, 1 (1950); *Angew. Chem.*, **60**, 113 (1948).
(5) Bernstein, J., Jambor, W. P., Lott, W. A., Pansy, F., Steinberg, B. A., and Yale, H. L., *Am. Rev. Tuberc.*, **67**, 354 (1953).
(6) Bernstein, J., Jambor, W. P., Lott, W. A., Pansy, F., Steinberg, B. A., and Yale, H. L., *Am. Rev. Tuberc.*, **67**, 366 (1953).
(7) Bernstein, J., Lott, W. A., Steinberg, B. A., and Yale, H. L., *Am. Rev. Tuberc.*, **65**, 357 (1952).
(8) Brownlee, G., *Intern. Congr. Microbiol., Rept. Proc., 4th Congr., Copenhagen, 1947*, 209 (1949).
(9) Brownlee, G., Green, A. F., and Woodbine, M., *Brit. J. Pharmacol.*, **3**, 15 (1948).
(10) Brownlee, G., *Ann. Repts. on Progress Chem. (Chem. Soc. London)*, **45**, 292 (1948).
(11) Buu-Hoi, N. P., Dechamps, G., Nguyen-Hoán, Le Bihan, H., Ratsimamanga, A. R., and Binon, F., *Compt. rend.*, **228**, 2037 (1949).
(12) Carr, D. T., Pfuetze, K. H., Brown, H. A., Douglass, B. E., and Karlson, A. G., *Am. Rev. Tuberc.*, **63**, 427 (1951).
(13) Chorine, V., *Compt. rend.*, **220**, 150 (1945).
(14) Chin, Y., Anderson, H. H., Alderton, G., and Lewis, J. C., *Proc. Soc. Exptl. Biol. Med.*, **70**, 158 (1949).
(15) Clark, C. M., Elmendorf, D. F., Jr., Cawthon, W. V., Muschenkeim, C., and McDermott, W., *Am. Rev. Tuberc.*, **66**, 391 (1952).
(16) Cornforth, J. W., Hart, P. D., Rees, R. J. W., and Stock, J. A., *Nature*, **168**, 150 (1951).
(17) Croshaw, B., and Dickinson, L., *Brit. J. Pharmacol.*, **5**, 178 (1950).

(18) Dennis, E. W., Goble, F. C., Berberian, D. A., and Frelch, E. J., *Ann. N.Y. Acad. Sci.*, **52**, 646 (1949).
(19) Domagk, G., *Proc. Colloq. Chemotherapy Tuberc.*, **1951**, 121.
(20) Domagk, G., Behnisch, R., Mietzsch, F., and Schmidt, H., *Naturwissenschaften*, **33**, 315 (1946).
(21) Donovick, R., McKee, C. M., Jambor, W. P., and Rake, G., *Am. Rev. Tuberc.*, **60**, 109 (1949).
(22) Emmart, W. H., and Smith, M. I., *Public Health Repts. (U.S.)*, **56**, 1277 (1941).
(23) Feinstone, W. H., Friedman, H. L., Rothlauf, M. W., Kelly, A. M., and Wilkans, R. D., *J. Pharmacol.*, **89**, 153 (1947).
(24) Feldman, W. H., *Proc. Colloq. Chemotherapy Tuberc.*, **1951**, 77.
(25) Feldman, W. H., Hinshaw, H. C., and Mann, F. C., *Am. Rev. Tuberc.*, **50**, 418 (1944).
(26) Feldman, W. H., Hinshaw, H. C., and Moses, H. E., *Proc. Staff Meetings Mayo Clinic*, **15**, 695 (1940).
(27) Fox, H. H., *J. Org. Chem.*, **17**, 555 (1952).
(28) Fox, H. H., and Gibas, J. T., *J. Org. Chem.*, **18**, 994 (1953).
(29) Francis, J., Spinks, A., and Steward, G. T., *Brit. J. Pharmacol.*, **5**, 549 (1950).
(30) Freire, S. A., Rist, N., and Grumbach, F., *Ann. Inst. Pasteur*, **81**, 407 (1951).
(31) Gardiner, P. A., Rees, R. J. W., and Robson, J. M., *Brit. J. Pharmacol.*, **4**, 209 (1950).
(32) Grunberg, E., and Leiwant, B., *Proc. Soc. Exptl. Biol. Med.*, **77**, 47 (1951).
(33) Grunberg, E., and Schnitzer, R. J., *Quart. Bull. Sea View Hosp.*, **13**, 3 (1952).
(34) Hamre, D., Bernstein, J., and Donovick, R., *Am. Rev. Tuberc.*, **59**, 675 (1950).
(35) Harington, C. R., Hart, P. D., and Rees, R. J. W., *Lancet*, **1**, 929 (1953).
(36) Heck, W. E., Lynch, W. J., and Graves, H. L., *Acta Oto-laryngol.*, **43**, 416 (1953).
(37) Hobby, G. L., Dougherty, N., Lenert, T. F., Hudders, E., and Kiseluk, M., *Proc. Soc. Exptl. Biol. Med.*, **73**, 503 (1950).
(38) Hoggarth, E., Martin, A. R., Storey, N. E., and Young, E. H. P., *Brit. J. Pharmacol.*, **4**, 248 (1949).
(39) Huebner, C. F., Marsh, J. L., Mizzoni, R. H., Mull, R. P., Schroeder, D. C., Troxell, H. A., and Scholz, C. R., *J. Am. Chem. Soc.*, **75**, 2274 (1953).
(40) Jenkins, D. E., *Trans. Chemotherapy Tuberc. Vet. Adm., 11th Conf.*, 309 (1952).
(41) Karlson, A. G., Gainer, J. H., and Feldman, W. H., *Diseases of the Chest*, **17**, 493 (1950).
(42) Karlson, A. G., and Feldman, W. H., *Am. Rev. Tuberc.*, **66**, 477 (1952).
(43) Karlson, A. G., and Feldman, W. H., *Ann. N.Y. Acad. Sci.*, **52**, 637 (1949).
(44) Kushner, S., Dalalian, H., Cassell, R. T., Sanjurjo, J. L., McKenzie, D., and Subbarow, Y., *J. Org. Chem.*, **13**, 834 (1948).
(45) Kushner, S., Dalalian, H., Sanjurjo, J. L., Bach, F. L., Jr., Safir, S. R., Smith, V. K., Jr., and Williams, J. H., *J. Am. Chem. Soc.*, **74**, 3617 (1952).
(46) Lee, H. F., and Stravitsky, A. B., *Am. Rev. Tuberc.*, **55**, 262 (1947).
(47) Lehmann, J., *Lancet*, **250**, 14 (1946).
(48) Levaditi, C., Girard, A., Vaisman, A., and Ray, A., *Compt. rend.*, **231**, 1174 (1950).
(49) Lurie, M. B., *Ann. N.Y. Acad. Sci.*, **52**, 627 (1949).
(50) McDermott, W., Ormand, L., Muschenheim, C., Deuschle, K., McCune, R. M., Jr., and Tompsett, R., *Am. Rev. Tuberc.*, **69**, 319 (1954).
(51) McKee, C. M., Rake, G., Donovick, R., and Jambor, W. P., *Am. Rev. Tuberc.*, **60**, 90 (1949).
(52) Marshak, A., *Science*, **106**, 394 (1947); *Public Health Repts. (U.S.)*, **62**, 3 (1947).
(53) Martin, A. R., *J. Pathol. Bacteriol.*, **58**, 580 (1946).
(54) Mayer, R. L., Esman, P. C., and Konopka, E. A., *Proc. Soc. Exptl. Biol. Med.*, **82**, 769 (1953).
(55) Meissner, G., and Hesse, E., *Naunyn-Schmiedeberg's Arch. expil. Pathol. Pharmakol.*, **147**, 339 (1930).
(56) Mertens, A., and Bunge, R., *Am. Rev. Tuberc.*, **61**, 20 (1950).
(57) Northey, E. H., *The Sulfonamides and Related Compounds*, Reinhold, N.Y., 1948, p. 523.
(58) Offe, H. A., Siefken, W., and Domagk, G., *Naturwissenschaften*, **39**, 118 (1952).
(59) Offe, H. A., Siefken, W., and Domagk, G., *Z. Naturforsch.*, **7b**, 462 (1952).
(60) Payne, H. M., Hackney, R. L., Domon, C. M., Marshall, E. E., Harden, K. A., and Turner, O. D., *Am. Rev. Tuberc.*, **68**, 103 (1953).
(61) Perry, T. L., *Proc. Soc. Exptl. Biol. Med.*, **72**, 45 (1949).
(62) *Quart. Progr. Rept. Vet. Adm., Army-Navy Study Chemotherapy Tuberc.*, October 1953, p. 80.
(63) Raiziss, G. W., Clemence, L. W., and Freifelder, M., *J. Am. Pharm. Assoc., Sci. Ed.*, **33**, 42 (1944).

(64) Rake, G., *Ann. N.Y. Acad. Sci.*, **52,** 765 (1949).
(65) Rake, G., and Donovick, R., *Am. Rev. Tubere.*, **60,** 143 (1949).
(66) Rake, G., Jambor, W. P., McKee, C. M., Pansy, F., Wiselogle, F. Y., and Donovick, R., *Am. Rev. Tubere.*, **60,** 121 (1949).
(67) Rake, G., McKee, C. M., Pansy, F., and Donovick, R., *Proc. Soc. Exptl. Biol. Med.*, **65,** 107 (1947).
(68) Raleigh, G. W., and Youmans, G. P., *J. Infectious Diseases*, **82,** 197 (1948).
(69) Rees, R. J. W., and Robson, J. M., *Brit. J. Pharmacol.*, **5,** 77 (1949).
(70) Rist, N., Block, F., and Hamon, V., *Ann. Inst. Pasteur*, **64,** 203 (1940).
(71) Robitzek, E. H., Selikoff, I. J., and Ornstein, G. C., *Quart. Bull. Sea View Hosp.*, **13,** 27 (1952).
(72) Rogers, E. F., Leanza, W. J., and Becker, H. J., *Science*, **116,** 253 (1952).
(73) Romansky, M. J., Ritts, R. E., Katz, S., and Marshall, E. E., *Trans. Conf. Chemotherapy Tubere. Vet. Adm. 12th Conf.*, 308 (1953).
(74) Rothstein, E., and Johnson, M., *Am. Rev. Tubere.*, **69,** 65 (1954).
(75) Sah, P. P. T., *J. Am. Chem. Soc.*, **75,** 2512 (1953).
(76) Sah, P. P. T., and Peoples, S. A., *J. Am. Pharm. Assoc., Sci. Ed.*, **42,** 612 (1953).
(77) Schaffeld, H. G., Garthwaite, B., and Amberson, J. B., *Am. Rev. Tubere.*, **69,** 520 (1954).
(78) Siebenmann, C. O., *Am. Rev. Tubere.*, **68,** 411 (1953).
(79) Smith, M. I., Jackson, E. L., and Bauer, H., *Ann. N.Y. Acad. Sci.*, **52,** 704 (1949).
(80) Solotorovsky, M., Seigel, H., and Ott, W. H., *Ann. N.Y. Acad. Sci.*, **52,** 696 (1949).
(81) Stephens, C. R., Conover, L. H., Hochstein, F. A., Regna, P. P., Pilgrim, F. J., Brunings, K. J., and Woodward, R. B., *J. Am. Chem. Soc.*, **74,** 4976 (1952).
(82) Titus, E., and Bernstein, J., *Ann. N.Y. Acad. Sci.*, **52,** 719 (1949).
(83) Urbanski, T., *Nature*, **166,** 267 (1950).
(84) Urbanski, T., Hornung, S., Slopek, S., and Venulet, J., *Nature*, **170,** 753 (1952).
(85) Waksman, S. A., *Streptomycin*, Williams and Wilkins, Baltimore, 1949, p. 279.
(86) Weiller, P., and Rymer, M., *Poumon*, **8,** 747 (1952).
(87) White, E. F., and Karlson, A. G., *Proc. Staff Meetings Mayo Clinic*, **23,** 52 (1948).
(88) White, H. J., *A Screening Test for Antituberculous Activity in Mice*, Gordon Research Conference, New London, New Hampshire, August 1952.
(89) Yale, H. L., Losee, K., Martins, J., Holsing, M., Perry, F. M., and Bernstein, J., *J. Am. Chem. Soc.*, **75,** 1933 (1953).
(90) Yeager, R. L., Munroe, W. G. C., and Dessau, F. I., *Am. Rev. Tubere.*, **65,** 523 (1952).

JACK BERNSTEIN

TUBES, ELECTRON. See *Electronics*, Vol. **5,** p. 558; *Vacuum tubes.*

TUBOCURARINE, TUBOCURARINE CHLORIDE, $C_{38}H_{44}Cl_2N_2O_6.5H_2O$. See *Alkaloids*, Vol. **1,** p. 490; *Stimulants and depressants*, Vol. **13,** p. 39.

TUCUM OIL. See *Fats and fatty oils*, Vol. **6,** pp. 144, 147.

TUKON MICROHARDNESS TEST. See *Hardness*, Vol. **7,** p. 365.

TUMERIC. See *Dyes*, Vol. **5,** p. 352.

TUNG OIL. See *Fats and fatty oils*, Vol. **6,** pp. 144, 147; *Drying oils.*

TUNGSTEN AND TUNGSTEN ALLOYS

Tungsten, W, atomic weight 183.92, atomic number 74, is in group 6 of the periodic table, below molybdenum, and between tantalum and rhenium horizontally. It is a silvery gray or tin-white metal. The naturally occurring isotopes are 182 (26.4%), 183 (14.4%), 184 (30.6%), and 186 (28.4%). Its chief valence numbers are +2, +3, +4, +5, and +6. See also *Tungsten compounds.*

The word tungsten is derived from the Swedish words *tung*, meaning heavy or ponderous, and *sten*, meaning stone, which calls attention to the high specific gravity. The origin of the word *wolfram* has been variously explained. Agricola in 1556 called tungsten ore *lupi spuma* (foam of the wolf) and the explanation of this is said to be that the mineral is generally discovered in conjunction with tin, which it "eats up as a wolf eats up sheep." *Lupus* is the Latin word for wolf and has been translated in the works of the metallurgists of Germany into their own *wolf* and *ram* meaning froth. It was not until 1781 that Scheele discovered and established beyond doubt the existence of calcium and an unknown acid in a mineral which is now known by his name: scheelite. To this unknown acid he gave the name tungstic acid. Tungsten metal was isolated by two Spanish chemists, the brothers D'Elhijar.

Recently, the name for element 74 has caused considerable controversy, especially in the United States. Based upon its desire for conformity between the names of elements and their international symbols, the XVth Conference of the International Union of Pure and Applied Chemistry, meeting in Amsterdam in September 1949, recommended that the English-language name tungsten be replaced by wolfram, which is the name for the element in most other languages. A second argument in favor of the change was based upon the similarity between the name wolfram and the name of one of the minerals from which it is obtained, wolframite. However, both British and American usage preferred the name tungsten. This led the subcommittee on inorganic nomenclature of the United States National Research Council, which is the official representative to the I.U.P.A.C., to issue a statement favoring the retention of the name tungsten, particularly in the face of the voluminous literature which exists under that name. In view of this, the April 1950 meeting of the I.U.P.A.C. Commission on Inorganic Nomenclature decided that both wolfram and tungsten be officially recognized as names for element 74. However, the following year, the Commission on Atomic Weights of the I.U.P.A.C. at its New York meeting in September recommended that the name wolfram be dropped from the periodic table because it failed to gain acceptance in the U.S.

It was not until 1909 that W. D. Coolidge was successful in making ductile tungsten from the metal powder by suitable heat treatment and mechanical working. Tungsten has two properties that make it of industrial importance. The first is its low vapor pressure at high temperatures, which makes it possible to take advantage of its high melting point; the second is its ability to harden metals with which it is alloyed. Tungsten tool steels have been a dominant factor in the era of mass production of machine-tool products. High-speed cutting steels take more of the tungsten stocks than any other use.

Of the tungsten reduced to metallic form, some is used for cemented carbides. While the tonnage use of tungsten as filament wire in incandescent lamps is small—1 or 2% of the annual total—it is indispensable. There is no known substitute for drawn tungsten wire in electric lamps.

Tungsten for all its high temperature qualities cannot be used for turbine blading. At steam- and gas-turbine temperatures, it forms a nonprotective oxide that soon leads to failure. Also its high density makes it undesirable for high rotating speeds.

Properties

The ordinary form of tungsten is body-centered-cubic. A face-centered cubic form, in which the atoms have two sets of special positions, may be formed by the elec-

trolysis of fused tungstates. If this modified form is heated above 700°C., it reverts irreversibly to the simple body-centered cubic form. The forms of tungsten have been designated α and β, but in an inconsistent manner. The lattice constant of body-centered cubic tungsten is $a_0 = 3.1647 \pm 0.00012$ A., that of the face-centered cubic form is 5.0510 ± 0.0002 A. (5.0408 ± 0.0002 kx) at 18°C.

Table I shows physical properties of tungsten (4).

TABLE I. Physical Properties of Tungsten.

Interatomic distance, A.	2.7407
Atomic radius (atomic coordination no. 8), A.	1.37
M.p., °C.	3410
B.p., °C.	5930
d_4^{20}	19.3
Sp.heat at 20°C., cal./g.	0.032
Latent heat of fusion, cal./g.	44
Latent heat of vaporization, cal./g.	1183
Vapor pressure, atm., at:	
3040°C.	0.001
4440°C.	0.01
5080°C.	0.1
5650°C.	0.5
Thermal expansion, linear	$L = L_0[1 + (4.28t + 0.00058t^2) \times 10^{-6}]$
Thermal conductivity, c.g.s. units, at:	
0°C.	0.40
100°C.	0.39
1250°C.	0.28
Electrical resistivity, microhm-cm., at 20°C.	5.5
Temperature coefficient of electrical resistivity, per °C., 0–170°C.	5.1×10^{-3}
Optical reflectivity at 5500A., %	50
Emissivity (spectral) at 4670A., at:	
1727°C.	0.469
2727°C.	0.455
3227°C.	0.449

The *mechanical properties* of tungsten are largely dependent on the previous history of the particular sample. The tensile strength of sintered rods (0.25 in. diameter) is about 18,000 p.s.i. Hot swaging increases the tensile strength to about 215,000 p.s.i. (0.026 in. diameter). The swaged rod when hot-drawn to 0.018 in. diameter wire has a tensile strength of 264,000 p.s.i. The tensile strength increases with further reduction by drawing until values as high as 590,000 p.s.i. are obtained for wire 0.0014 in. in diameter. Fine tungsten wire has the highest tensile strength of any known material. The compressibility of tungsten is about 1.67×10^{-3} t.s.i., the smallest value for all the metals.

As tungsten wire is progressively drawn to finer sizes, the elastic modulus increases from 12.8×10^6 to 55×10^6 p.s.i. The fact that the modulus varies probably is the result of changes in crystal orientation texture. The low initial modulus reflects fabrication variables, such as amount of sintering and pressing.

Tungsten is a relatively hard metal. Sintered bars of tungsten have a hardness of about 255 Vickers; swaged rods have hardnesses as high as 488 Vickers. As the metal is progressively cold-worked, the metal increases in hardness:

Sheet 0.04 in. thick	45 Rockwell C
Sheet 0.01 in. thick	67 Rockwell C
Rod 0.25 in. diam.	37 Rockwell C
Rod 0.10 in. diam.	40 Rockwell C

The hardness of cold-worked tungsten is reduced slightly when the metal is annealed.

The tensile elongation of cold-worked tungsten ranges from 0 to 4%. The metal is generally brittle when fully recrystallized. Single-crystal thoriated wire has an elongation of about 20%. The elongation of tungsten wire increases slightly with increasing temperature up to about 2200°F.

The modulus of torsion varies from 12.8×10^6 to 31.3×10^6 p.s.i. at 68°F., depending on crystal orientation texture.

Recrystallization and Grain Growth. Commercial tungsten generally becomes brittle if the recrystallization temperature is exceeded to the extent that the grains of the metal are equiaxed. The recrystallization temperature of tungsten varies. It is established that, in general, the recrystallization temperature of tungsten is lowered markedly by the degree of cold working applied to the metal. The recrystallization temperature ranges from about 2820°F. down to a dull red heat for fine wire. Recrystallization is accompanied by a decrease in both tensile strength and ductility, and the wire eventually becomes quite brittle.

Additives to tungsten are used to restrict grain growth or to promote grain growth in certain directions of the wire products. The addition of 0.4% KCl, 0.4% SiO_2, and 0.1% Al_2O_3 to tungsten oxide before reduction to the metal is the favored addition for preparing nonsag wire for lighting purposes. Most of this "dope" volatilizes during sintering at about 3000°C., and the recrystallized wire obtained after swaging and drawing shows the peculiar grain formation of coarse grains which are interlocked or keyed together. The grains are equal to the diameter of the wire, and the interlocking prevents slipping or offsetting of the grains with respect to each other. This property markedly extends the life of the filament. On the other hand, the addition of a nonvolatile material such as thorium oxide (about 0.75% ThO_2) prevents grain growth, resulting in a fine-grained material even after heating to elevated temperatures.

Reactions (3). Tungsten is not affected by air at room temperature when the metal is in other than powder form. If in the form of finely divided powder, it may be pyrophoric. Tungsten begins to oxidize appreciably at 750°F.

Tungsten resists water and water vapor at room temperature but is oxidized rapidly at red heat. It is attacked quite readily by molten sodium nitrite, and this may be used for etching or pointing rod or wire for drawing.

Dry chlorine, free from air, attacks tungsten at about 250–300°C. forming the hexachloride, but if air or moisture is present the oxychlorides are formed. Fluorine reacts with tungsten at ordinary temperatures. The pentabromide is formed at red heat in the absence of moisture. The diiodide is formed when tungsten at red heat is treated with iodine.

Tungsten is not attacked by hydrofluoric acid. Warm nitric acid easily oxidizes tungsten to the yellow trioxide, WO_3. Hot concentrated hydrochloric acid and hot concentrated sulfuric acid react only slightly with the metal. A mixture of nitric and hydrofluoric acids acts on tungsten with the formation of the trioxide. Aqua regia causes superficial oxidation at room temperature. Table II gives the chemical resistance of sintered tungsten.

TABLE II. Chemical Resistance of Sintered Tungsten.

Corrosive agent, 10% soln.	Time, hr.	Wt. loss, g./sq.dm.
Nitric acid, cold	24	0.0
Nitric acid, hot	1	0.06
Sulfuric acid, cold	24	0.0
Sulfuric acid, hot	1	0.01
Hydrochloric acid, cold	24	0.0
Hydrochloric acid, hot	1	0.01

Tungsten is resistant to molten sodium hydroxide, but the presence of potassium nitrate, potassium nitrite, potassium chlorate, lead dioxide, or other oxidants in the hydroxide will cause rapid corrosion. Alkali solutions and ammonia do not corrode tungsten in the absence of oxygen.

The gases, carbon dioxide, carbon disulfide, sulfur, carbon monoxide, nitric oxide, and nitrogen dioxide react with tungsten at high temperatures. Molten sulfur and phosphorus attack the metal slowly, while the vapors of these elements react with it vigorously. Carbon, boron, and silicon form compounds with tungsten at high temperatures. Nitrogen does not attack tungsten up to 1500°C. but the dinitride is formed when nitrogen is present in an incandescent tungsten filament at 2300°C. Tungsten metal is not attacked by hydrogen. Molten nitrates, nitrites, and peroxides react violently with tungsten.

Analysis. In qualitative analysis, tungsten is usually converted into a tungstate. A white amorphous precipitate of hydrated tungstic acid is obtained by treating the tungstate solution with acids; upon boiling, the yellow anhydrous acid is obtained. If the solution of an alkali tungstate is treated with hydrochloric acid and zinc or aluminum or tin, it turns a beautiful blue. Ferrous sulfate gives a yellowish-brown precipitate which is not turned blue by acid. Lead acetate, barium chloride, and silver nitrate also precipitate white tungstates.

In quantitative analysis, the most satisfactory method for determining tungsten is based upon its separation as the slightly soluble tungstic acid. This is accomplished by digesting the tungstate solution with hydrochloric acid or nitric acid. Since there is some residual tungsten left in the filtrate, a second precipitation, generally in the presence of cinchonine hydrochloride, is necessary. The cinchonine hydrochloride forms cinchonine tungstate which is insoluble in cold dilute hydrochloric acid. Its presence also prevents the formation of the acid tungstate and of colloidal solutions upon washing. These precipitates are then combined and carefully ignited to the trioxide, WO_3, which is weighed. Since the trioxide is volatile above 750°C., the ignition should not be prolonged nor carried out at too high temperatures.

Occurrence

Although tungsten is one of the rarer elements, comprising only approximately $5 \times 10^{-5}\%$ of the earth's crust, some fairly rich tungsten-producing areas have been discovered. Economically, the most important of these is the China-Malaya area which, in the period between 1913 through 1937 produced 62.6% of the metal. The second area of importance is in the western portion of North America and comprises most of the western states, Alaska, and Mexico. However, only 10.8% of the world's supply was produced in North America during the same period.

The ores of commercial importance are of two general types, scheelite and wolframite. *Scheelite* is calcium tungstate, $CaWO_4$, containing, when pure, 80.6% WO_3, the commonest impurity being MoO_3, which is not an objectionable impurity for the manufacture of alloy steels, but is highly undesirable in making lamp filaments. The scheelite deposits are crystalline, white, yellow, or reddish in color, but never dark; the crystals are soft, easily scratched with a knife, hardness = 4.5, and the specific gravity is about 6, making mechanical separation easy.

Wolframite is essentially a tungstate of Fe(II) and Mn(II), $(Fe,Mn)WO_4$, of varying proportions. Technically samples of ore which contain more than 20% FeO are called *ferberite*, while those containing more than 20% MnO are known as *hübnerite*, and intermediate materials are called wolframite. However, especially in the absence of accurate analyses, the term wolframite is practically used to cover all materials in the series. The mineral is either crystalline or granular in form, always dark in color, with a tendency toward brown in hübnerite and shining black in ferberite. The mineral is soft enough to be scratched with a knife, hardness = 5.5, is very brittle, and shows perfect cleavage, breaking into thin, lustrous flakes. The specific gravity is about 7.5, equal to galena and greater than cassiterite, with which it is commonly associated in nature.

Wolframite generally occurs in veins in granitic rocks and in metamorphic rocks close to granitic intrusives. Quartz is the commonest gangue mineral; cassiterite is commonly present, and native bismuth, bismuthinite, molybdenite, and scheelite are occasionally present. Scheelite is most commonly mined from contact metamorphic deposits in limestone near granitic intrusives; garnet, vesuvianite, and fluorite are commonly present.

Tungsten ore in the U.S. occurs underground in low concentrations, 0.5–3%. The grade is generally less than 1%; ore running 3% is considered high-grade and is rare.

Concentration of Ore. Since the ores contain at best only 2–3% W, the first problem is to produce a concentrate. This is done by crushing the ore to a fine powder and by various gravity separations and/or by flotation. The object of the beneficiation of tungsten ore is to produce a concentrate containing at least 60% WO_3. Since cassiterite, that is, tin oxide, is frequently found associated with tungsten ores, magnetic separators have proved especially useful in separating these two minerals. Wolfram is feebly magnetic while cassiterite is nonmagnetic. However, this method is not applicable to the separation of tin from scheelite concentrates since, in this case, both minerals are nonmagnetic.

Manufacture

Preparation of Oxide. Pulverized wolframite is mixed with the desired amounts of dry soda ash and sodium nitrate and mixed intimately in a pebble mill. Then the mixture is fed into a tilted, rotary furnace and maintained at a temperature of 1020–1040°C. The use of an oxidizing agent, such as sodium nitrate, in the melt facilitates the oxidation of the iron and manganese content of the ore. The fused charge is fed slowly into a lixiviating tank and the insoluble material is removed by filtering. The tungsten is recovered either by crystallization as sodium tungstate or by precipitating with hydrochloric acid. An alternate procedure is to digest the pulverized wolframite in a boiling aqueous caustic soda solution. The soluble sodium tungstate is filtered

off from the insoluble hydrated oxides of iron and manganese. The sodium tungstate is converted to tungstic acid by the addition of hydrochloric acid.

In the production of ductile tungsten it is necessary to remove practically all mineral impurities. The method used is known as the precipitated ammonium paratungstate process and brings the tungsten oxide content up to 99.97%. The tungstic acid is washed, filtered, and converted to ammonium paratungstate by the addition of water and ammonium hydroxide and filtering off any residue. The ammonium salt is evaporated and the residue dried and treated repeatedly with nitric acid. Finally the acid is heated in vitreous silica ware at 1000°C., when the trioxide is obtained as a powder. The coarseness of the trioxide powder may be controlled by regulation of the time and temperature of ignition and the purity of the material. The physical condition of the powder is of great importance since it determines in large measure the working properties of the metal obtained from it.

Reduction. The oxide is then reduced to the metal by heating in hydrogen. By suitably arranging the conditions of reduction, the metal powder can be varied from a fine black pyrophoric material (mean diameter of particles is less than 0.5μ) to coarse metal crystals up to 500μ in diameter. Most modern methods of working tungsten demand a fine metal powder of a gray-black color with an average particle size of about 2.5 microns.

Fineness of the metal powder is controlled by the time and temperature of reduction. In order to produce a more uniform product it is common practice to carry out the reduction in two stages. The first stage produces the brown oxide, WO_2, which is then mixed with an equal weight of yellow oxide, WO_3, and the reduction is completed at a slightly higher temperature. The temperature gradient during the first stage of the reduction is from 500 to 700°C.; temperature gradient for the second stage is 650–800°C. The boats containing the tungsten oxide move countercurrent to the hydrogen flow.

Powder Metallurgy (*q.v.*). The properties of tungsten are such that the metal is generally produced by powder metallurgy methods. Tungsten powder is compacted in dies by use of a hydraulic press. Pressures of about 25 t.s.i. are employed. After pressing, the fragile compacts are presintered at 1800–2200°F. in hydrogen. This strengthens the compacts so that they can be handled easily and machined if necessary. The presintered bars are given a final sinter in a hydrogen atmosphere. In this operation the bars are heated by passing a current through them. The maximum current used is about 95% of the current required for fusing the bar, causing a temperature of about 3000°C. The sintered bars have a density of about 17 g./cu.cm. and can be ground and polished for certain uses.

Preparation of Rods, Sheet, and Wire. The tungsten bar is worked into rod by swaging. In this process it is heated to about 1600°C. in an atmosphere of hydrogen and fed slowly between the rotating hammers of the machine. The temperature at which the wire is worked is reduced steadily as the diameter decreases. As the swaging continues, the temperature is gradually reduced to about 800°C. and as the bar elongates it is found that the crystals themselves become longer and longer. If ductile tungsten is desired, the swaging is continued until a diameter of about 0.04 in. is obtained. The resulting rods can be drawn to finer sizes by heating and drawing on a chain bench to about 0.028 in. diameter. At this stage, the wire has sufficient ductility to permit coiling and the use of power-driven reels. Drawing temperatures are reduced gradually as the wire becomes progressively finer in size.

With care, sintered or swaged tungsten can be rolled. High temperatures are used in the early stages of rolling and the ductility of the metal is increased by the rolling operation. Because of oxidation, it is difficult to roll tungsten to thicknesses less than 0.004 in. by ordinary methods; however, 0.00012 in. sheet has been produced by cladding the tungsten with iron.

Tungsten is not readily forgeable but sintered bars can be forged when heated to 3270°F.; the temperature is reduced toward the end of the operation to 2000°F. Generally, sintered bars of tungsten are hot-swaged rather than forged.

Joining. Silver and soft solders are used to solder tungsten. Tungsten can be brazed using copper, nickel, copper-nickel alloys, and conventional brazing equipment. For high-temperature use, tantalum is used as the braze. At present, welds in tungsten are likely to be brittle at room temperature since oxidation is a problem in the welding of tungsten. Spot welds are commonly made using a layer of nickel between the tungsten parts.

Melting and Casting. Because of its high melting point, little work has been done on the melting and casting of tungsten. Tungsten has been melted as droplets from arc electrodes and from resistance-heated bars. Recently, the vacuum-arc method has been used to make tungsten ingots. No important commercial development of melting and casting tungsten has been made, although it has been demonstrated that forgeable arc-melted ingots can be prepared.

Machining. Machining of tungsten is difficult and is not recommended. Finishing and cutting operations should be performed by the use of abrasive wheels; silicon carbide wheels are the most satisfactory for all types of grinding. In grinding, care must be exercised to avoid chipping or cracking.

Cleaning and Finishing. Conventional methods can be used to degrease tungsten parts that have been formed in a reducing atmosphere. If the parts have been heated in air, the oxide coating which develops is removed by electrolytic caustic cleaning or by immersion of the parts in molten caustic soda for a few seconds, draining, cooling, and rinsing in hot running water. Since molten caustic soda attacks tungsten, the time of immersion should be held to a minimum. Parts can also be fired in hydrogen to reduce the oxide. Tungsten can be polished electrolytically to obtain a bright finish using a 10% solution of sodium hydroxide.

Manufacture of Ferrotungsten. Although both the aluminothermic and silicothermic processes have been used in the past to produce ferrotungsten, present practice is based upon reduction of the ore by coke in an electric furnace. Generally, the tungsten charge is composed of 70% wolfram, 25% scheelite, and 5% ferberite, although other proportions can be used provided that the iron-tungsten ratio is such that a product having a tungsten content of 70% or higher is obtained. Owing to the high melting point of the product, tapping the melt has not proved successful and a "knock-down" furnace is necessary making the process discontinuous. After the reaction is completed and the furnace cooled, the outer steel shell and liner are removed and the metallic button formed is broken up.

In recent years, however, there has been a general trend toward the use of high-purity tungsten concentrates, especially scheelite, instead of the ferroalloy by the steel industry due to the disadvantages of high-melting ferrotungsten. As an example, in 1945, 50% of the total tungsten consumption was in the form of ferroalloy and only 13% in the form of high-purity concentrates. However, in 1946, consumption as ferrotungsten was decreased to 35% while that of tungsten concentrates was increased to 28%.

Economic Aspects

The following is the most recent economic information (as of December, 1954) which has been released by the Bureau of Mines concerning tungsten. Owing to the work required to gather and compile these figures, a certain time lag exists. In addition, many of the figures concerning world production are, by necessity, estimations. The principal source used is *Minerals Yearbook*, 1951, which is published by the Bureau of Mines.

Tungsten production in the China-Malaya area in 1951 was estimated at 37.3% of the world's production while the North American area produced 12.0%. Estimated world production of tungsten in 1951 was 26,276 short tons of which 2,957 tons were produced in the U.S. This is approximately 11.4% of the world's production. The major tungsten producing countries, in 1951, were as follows: China 31.5%, U.S.S.R. 15%, U.S. 11.4%, Portugal 9.3%, Bolivia 5.4%, Spain 4.6%, Australia 3.7%, Burma 3.3%, and Korean Peninsula 2.2%. Estimated world production of tungsten in 1952 was 29,056 short tons of which 3,616 tons or 12.4% were produced in the U.S.

In the U.S., the five major tungsten-producing states were California, Nevada, North Carolina, Idaho, and Colorado. In 1951, these states produced 1,187, 914, 492, 191, and 155 short tons of tungsten, respectively. This accounts for approximately 99% of the U.S. production.

Although the U.S. was the third largest tungsten-producing country in 1951, domestic supplies were insufficient to meet all U.S. industrial needs. This required the importation of 3,188 short tons of tungsten in 1951 and 4,141 short tons in 1952. In addition, although exact figures are not yet available, the indications are that this amount more than doubled in 1953 and increased still farther during 1954. Table III lists the amount of tungsten imported to the U.S. from various sources in 1951.

TABLE III. Tungsten Imported to U.S., 1951.

Country	Per cent of total tungsten imports	Imported to U.S., short tons
Portugal	16%	499
Australia	13%	423
Thailand	12%	369
Korea	11%	352
Bolivia	11%	346
Brazil	10%	309
Spain	7%	234
Peru	5%	173
Argentina	4%	148
Burma	4%	145
Japan	2%	78
Mexico	2%	76

Table IV lists the consumption of tungsten in the U.S.

The current prices for tungsten ore are: imported wolframite concentrate, $24–25 plus $7.90 duty per net short ton unit; domestic scheelite concentrate, $63 per net short ton unit. Each short ton unit is equivalent to 20 lb. of WO_3 and therefore contains 15.862 lb. of tungsten. The prices of the ores listed above when converted to dollars per pound of contained tungsten are: imported wolframite concentrate,

$2.01–$2.07/lb. of contained tungsten; domestic scheelite concentrate, $3.97/lb. of contained tungsten.

TABLE IV. Consumption of Tungsten in U.S.

Year	Ferrotungsten, short tons W	Per cent	Concentrates for steel, short tons W	Per cent	Metal powders and others, short tons W	Per cent
1946	1142	35	904	28	1190	37
1948	1951	44	880	20	1594	36
1950	554	17	935	28	1808	55
1951	1099	19	618	11	3987	70

Uses

The chief use of tungsten is in the manufacture of ferrous tungsten alloys and tungsten carbide, the former accounting for about 90% and the latter for about 5% of the yearly consumption of tungsten in the U.S.

Pure Tungsten. Although the use of tungsten for the manufacture of filament wire for incandescent lamps and for rods, contacts, and other electrical uses represents only about 1–2% of total annual consumption, this use is extremely important. Tungsten is used as lead-in wire for power tubes (tungsten and hard glass have nearly the same coefficient of thermal expansion) and for certain elements in electronic tubes. Tungsten filaments containing 2% thorium are used as cathodes for power electronic tubes. See *Lamp manufacture (electric)*; *Vacuum tubes.*

Because of its high elasticity, tungsten wire is particularly suitable for suspending mirrors in galvanometers and for crosshairs in telescopes.

Ferrous Alloys. Innumerable ferrous alloys in wide usage contain up to 20% tungsten as an addition. The tungsten enables the steel to resist the effects of high temperature and forms hard, wear-resistant carbides in the steel. Prominent among these tungsten-steel tools is the so-called 18-4-1 high-speed steel whose composition is W, 18%; Cr, 4%; and V, 1%. The percentage of vanadium may vary up to 3% with or without the addition of cobalt. The high-speed steels (18% W) are the most widely used tungsten-containing steels. The main characteristic of high-speed steel tools is that they maintain a sharp cutting edge at working temperatures far above those that ruin carbon-steel tools. This property is generally known as *red-hardness.* In addition, the tungsten in high-speed tool steels imparts to them a cutting or lathe efficiency approximately five times that of ordinary carbon steel. Hot-work steels (10% W) are used in operations where a minimum loss of hardening is desired when the steel is used at about the tempering temperature. Tungsten hot-work steels generally retain considerable hardness up to about 1150°F., while ordinary chrome steels have a temperature limit of about 800°F. Finishing steels (3.5% W) possess extreme wear resistance or abrasion resistance, whereby a keen cutting edge can be retained. These steels, however, are not designed for high-temperature operations and a service temperature greater than 300°F. is not recommended. Tungsten is added to other steels for various reasons, for example, creep resistance, high strength at elevated temperatures, and high density.

Ferrous alloys other than tool steels are the tungsten magnet steels and tungsten stainless and heat-resisting steels. Some tungsten magnet steels contain only a few percentages of tungsten and chromium while others contain high percentages of cobalt, besides the usual percentage of tungsten and chromium. See *Magnetic substances.*

The tungsten stainless and heat-resisting steels are used for exhaust valves of aircraft engines, bolts, and turbine parts, and distilling tubes in oil refineries. Their composition varies according to use.

Nonferrous Alloys. Of the nonferrous alloys, Stellite, a Co-Cr-W alloy is the most important. A typical form of Stellite has an approximate analysis 48–53% Co, 28–32% Cr, 12–16% W, and 2.5% C. Because these alloys possess good resistance to corrosion and wear, they find use in equipment for handling acids and other chemicals, excavating equipment, dies and punches, and shears for hot metals.

Copper-tungsten and silver-tungsten alloys are used as materials for switches, circuit breakers, and other switch-gear. Two-typical commercial alloys of this type are Elkonite (10-W-3), containing 77% W and 24% Cu, and Gibsaloy Grade W, 30–90% Ag, balance W. The so-called *heavy metal* is a tungsten-nickel-copper alloy containing 3.5–16.5% Ni, 1.5–13.5% Cu, and 83–95% W. Because of its high density, it is largely used as material for radium containers and rotors of gyroscopes.

Tungsten Carbide. Tungsten carbide is prepared by the reaction of tungsten or tungsten oxide with carbon at a high temperature (1500–1600°C.) in an inert atmosphere. The resulting carbide is crushed to a powder and mixed with cobalt powder which acts as a cementing agent when the product is sintered. The result is a cemented tungsten carbide that approaches the diamond for hardness. Because of its high hardness and transverse strength, tungsten carbide is a component of hard materials used for dies, tools, and wear-resistant parts, and has become important as a material for insert bits used in rock drilling. Various materials containing tungsten carbide are available. The straight tungsten carbide with cobalt binder is used in tools for cutting cast iron, nonferrous metals, and nonmetallic materials and in dies for drawing wire, bar, tube, and sheet metal for blanking as well as for machine parts where resistance to wear is important. The steel-cutting grades consist largely of tungsten carbide with additions of titanium carbide or tantalum carbide or both. These added constituents produce a material that resists cratering better than any of the straight tungsten carbide grades.

Recently, a new method has been developed which permits the formation of tungsten carbide coatings on steel. The process utilizes an inert-gas-shielded arc which melts the base metal producing an elongated pool. Tungsten carbide particles from a vibratory hopper are poured into this pool behind the arc, the molten metal freezing around the particles. Of particular advantage in this process is the speed which can be attained in production without sacrifice in the quality of the coatings. Use of tungsten carbide coatings on steel, known as hardfacing, has been of particular benefit in applications involving tool joints for well-drilling rigs which are subjected to severe earth and rock abrasion.

Bibliography

(1) Everhart, J. L., *Materials and Methods*, **34**, No. 6, 99–101 (1951).
(2) Hopkins, B. S., *Chapters in the Chemistry of Less Familiar Elements*, Stipes, Champaign, Ill., 1939, ch. 17.
(3) Li, K. C., and Wang, C. Y., *Tungsten*, Reinhold, N.Y., 1947.
(4) *Metals Handbook* **1948**, Am. Soc. Metals, Cleveland, pp. 20, 21, 173, 656–59, 1144.
(5) Scarlott, C. A., *Materials and Methods*, **34**, No. 3, 72–73 (1951).
(6) Smithells, C. J., *Tungsten*, Chapman & Hall, London, 1945.
(7) Wang, C. Y., *Mining Engineering*, **3**, No. 10, 853–56 (1951).

BERNARD KOPELMAN

TUNGSTEN COMPOUNDS

The chemistry of tungsten and its compounds is very similar to that of both molybdenum and chromium, the other two elements in the same subgroup of Group VI of the periodic table. Several states of oxidation exist for tungsten, and compounds in which tungsten has a value of 0, +2, +3, +4, +5, and +6 are known. The lower valence states, however, are relatively unstable, and bivalent tungsten is known only in simple halogen compounds. The most stable, and therefore the most common, valence state of tungsten compounds is +6. In general, the chemistry of tungsten is quite complex. This is due primarily to the strong tendency for complex formation, exemplified by the large number of heteropoly acids formed with the oxides of phosphorus, arsenic, vanadium, silicon, and others. In addition, there are compounds, particularly the oxides, in which tungsten exists in more than one valence state.

Tungsten Arsenide.

Tungsten diarsenide, WAs_2, is obtained as a black, crystalline mass by heating tungsten hexachloride in a current of arsine, AsH_3, at 350°C. The product has a specific gravity of 6.9 (at 18°C.) and is stable in air at ordinary temperatures. When heated in air, tungstic oxide is easily formed. The arsenide is also attacked by chlorine, sulfur, phosphorus, and fused alkalies and alkali carbonates. It is not soluble in water and is inert toward hydrofluoric and hydrochloric acid solutions. Hot nitric acid or aqua regia, however, attacks it, forming tungstic acid.

Tungsten Borides.

Ditungsten boride, W_2B, forms tetragonal crystals with $a = 5.564$, $c = 4.740$, space group D_{4h}^{13}, sp.gr. 15.98, m.p. 2770 ± 80°C.

Tungsten monoboride, WB, forms tetragonal crystals with $a = 3.115$, $c = 16.93$, sp.gr. 15.41, m.p. 2860 ± 80°C. At 1850 ± 50°C., it undergoes a phase transition becoming orthorhombic with $a = 3.19$, $b = 8.40$, and $c = 3.07$.

Tungsten diboride, WB_2, forms silvery, metal-like octahedral crystals, sp.gr. 10.8. It is insoluble in water but is attacked by concentrated acid. Chlorine will also decompose it at 100°C., as will a fused mixture of sodium carbonate and sodium nitrate.

Tungsten Bronzes. See p. 370.

Tungsten Carbides.

Tungsten and carbon form two binary compounds, **tungsten carbide,** WC, hexagonal crystals with $a = 2.910$ and $c = 2.838$, sp.gr. 15.7, and **ditungsten carbide,** W_2C, sp.gr. 16.06, both of which are prepared by heating together tungsten and carbon at about 1500–1600°C. Both form gray powders, melt at approximately 2800°C., and have a hardness approaching that of the diamond. These compounds are insoluble in water, but they are readily attacked by a mixture of HNO_3–HF. Carbides corresponding to W_3C, W_3C_2, and W_3C_4 have been reported but their existence has not been confirmed. See also p. 362; *Carbides (heavy-metal)*, Vol. **2**, p. 846.

Tungsten Carbonyl.

Tungsten hexacarbonyl, $W(CO)_6$, formula weight 351.98, is a white, volatile crystalline solid which decomposes without melting at approximately 150°C. At

room temperature, its vapor pressure is of the order of 0.1 mm. Hg. It is fairly stable in air, water, or acid, but it is decomposed in strongly basic solutions and is attacked by the halogens. Tungsten carbonyl is nontoxic, and somewhat soluble in organic solvents but insoluble in water. It is prepared by reaction of tungsten metal with carbon monoxide at 275–300°C. under a pressure of 200 atm. Another method has also been reported based upon the reduction of tungsten hexachloride by aluminum in anhydrous ether under a pressure of 100 atm. of carbon monoxide at 70°C.; yields of over 90% of theoretical were obtained. The use of tungsten carbonyl as a method for obtaining tungsten coatings on base metals through the deposition and decomposition of the carbonyl vapor is being investigated. The deposited metal is usually contaminated with carbide. See also *Carbonyls*.

Tungsten Halides and Oxyhalides.

Tungsten halides are known to exist in the +2, +3, +4, +5, and +6 valence states. In general, they are characterized by their instability toward both air and moisture and by their low boiling points. The volatility of these compounds, particularly the hexachloride, makes them suitable starting materials for the formation of tungsten coatings on base metals by a vapor-deposition process, or for the formation of single-crystal tungsten wires as described by de Boer and van Arkel (1).

Tungsten dichloride, WCl_2, formula weight 254.83, is unstable in air in the presence of water, forming tungsten dioxide and liberating hydrogen chloride. It may be prepared as a gray amorphous powder by the reduction of tungsten hexachloride by hydrogen.

Tungsten tetrachloride, WCl_4, formula weight 325.75, is a dark brown nonvolatile crystalline powder, sp.gr. 4.624, which is hygroscopic, forming tungsten dioxide and hydrogen chloride in cold water. It is generally prepared by the partial reduction of tungsten hexachloride by hydrogen. Gentle action of hydrogen on tungsten hexachloride, however, produces **tungsten pentachloride,** WCl_5, as dark green or black deliquescent crystals, formula weight 361.21, sp.gr. 3.875, m.p. 248°C., b.p. 275.6°C. The pentachloride is slightly soluble in carbon disulfide but decomposes in water forming the blue oxide, W_2O_5.

Tungsten hexachloride, WCl_6, formula weight 396.66, exists in the form of dark blue or violet hexagonal crystals, $a = 6.088$, $c = 16.68$, space group C_{3i}^2, m.p. 275°C., b.p. 346.7°C., sp.gr. 3.52. Generally, it is prepared by treating tungsten metal with pure, dry chlorine gas at red heat. In the presence of moisture or oxygen, however, some $WOCl_4$ is formed as an impurity. The hexachloride is very soluble in carbon disulfide but decomposes in water, forming tungstic acid. It is easily reduced by hydrogen to the lower halides, and finally to the metal itself.

Tungsten dioxydichloride, WO_2Cl_2, is a pale yellow solid, formula weight 286.83, m.p. 266°C. It is soluble in cold water and in alkaline solution although it is partly decomposed by hot water. It may be prepared by the action of chlorine gas on heated tungstic oxide. This oxychloride is not decomposed in the presence of moist air but is easily reduced to metal when heated in a current of dry hydrogen.

Tungsten oxytetrachloride, $WOCl_4$, forms red needles, sp.gr. 11.92, m.p. 211°C., b.p. 227.5°C. It is soluble in carbon disulfide, slightly soluble in benzene, and is decomposed to tungstic acid by water. It may be prepared by passing chlorine over an equimolar mixture of tungsten and tungsten dioxide at 300–500°C., with a yield of

87–88% of theoretical. The product is purified by vacuum distillation at 200–210°C. A mixture of both oxychlorides is formed by the action of chlorine on tungsten dioxide.

Tungsten dibromide, WBr_2, *formed by the partial reduction of the pentabromide* by hydrogen, is a bluish-black powder decomposing at 400°C.

Tungsten pentabromide, WBr_5, forms dark brown needles, m.p. 276°C., b.p. 333°C. It may best be prepared by the action of bromine, preferably diluted with carbon dioxide, on tungsten metal at red heat. However, the presence of air or moisture must be avoided or some oxybromide will be formed. Hydrogen reduces the pentabromide to the dibromide at 350°C. and to the metal at higher temperatures.

Tungsten hexabromide, WBr_6, bluish-black crystals, is formed by gently heating tungsten metal in bromine vapor in the absence of air or moisture.

Tungsten Oxybromides. Two oxybromides of tungsten are known, the *dioxydibromide*, WO_2Br_2, light red crystals, and the *oxytetrabromide*, $WOBr_4$, dark brown or black deliquescent needles, m.p. 277°C. b.p. 327°C., Both are formed by the action of tungsten pentabromide on heated tungstic oxide and may be separated by distillation.

Tungsten diiodide, WI_2, formula weight 437.76, is a brown powder, sp.gr. 6.9 (18°C.). It may be prepared by the action of iodine vapor on tungsten metal at red heat or by treating tungsten hexachloride with anhydrous hydrogen iodide at 400–450°C. Tungsten diiodide is insoluble in cold water, alcohol, and carbon disulfide but is decomposed by hot water.

Tungsten tetraiodide, WI_4, is a black powder, which is decomposed by air. It may be prepared by the action of concentrated hydriodic acid on tungsten hexachloride at 100°C.

No tungsten oxyiodides have been prepared.

Tungsten trifluoride, WF_3, is not known as such. However double salts (fluotungstates(III)) are known, such as $KF.WF_3.H_2O$ and $NH_4F.WF_3.H_2O$.

Tungsten hexafluoride, WF_6, formula weight 297.92, is a colorless gas at room temperature, sp.gr. 10.35 with respect to air. At 19.5°C., the hexafluoride condenses into a pale yellow liquid, and at 2.5°C. a white solid is formed. It may be prepared by treating either hydrogen fluoride, arsenic trifluoride, or antimony pentafluoride with tungsten hexachloride:

$$WCl_6 + 6\,HF \longrightarrow WF_6 + 6\,HCl \quad (1)$$

$$WCl_6 + 2\,AsF_3 \longrightarrow WF_6 + 2\,AsCl_3 \quad (2)$$

$$WCl_6 + 3\,SbF_5 \longrightarrow WF_6 + 3\,SbF_3Cl_2 \quad (3)$$

Methods (1) and (2) must be carried out in a platinum retort but glass apparatus may be used with method (3). Tungsten hexafluoride may also be formed by the action of fluorine gas on metallic tungsten at ordinary temperatures. Tungsten hexafluoride is extremely unstable in the presence of moisture, hydrolyzing completely into tungstic acid:

$$WF_6 + 4\,H_2O \longrightarrow H_2WO_4 + 6\,HF$$

When tungsten hexafluoride is dissolved in organic solvents such as benzene and cyclohexane, the solution becomes bright red, while a pale red is obtained in dioxane, and violet-brown in ether and diethyl Carbitol, $(C_2H_5OC_2H_4)_2O$. Reduction of the hexafluoride by benzene to produce **tungsten tetrafluoride,** WF_4, has been reported, the reaction taking place in a nickel bomb at 110°C. over a period of 3–9 days. The

compound has been described as a reddish-brown solid, somewhat hygroscopic and hydrolyzed by hot alkali to hydrous tungsten dioxide and by an acid solution to tungsten trioxide.

Tungsten oxydifluoride, WOF_2, is chemically inert, resisting boiling alkali, concentrated acid, and aqua regia. However, it may be ignited to tungsten trioxide by heating in air at 700°C. It is prepared as a gray solid by action of anhydrous hydrogen fluoride on tungsten dioxide at 500°C.

Tungsten oxytetrafluoride, WOF_4, formula weight 275.92, exists in the form of colorless plates, m.p. 110°C., b.p. 187°C. This compound is extremely hygroscopic, decomposing into tungstic acid in the presence of water. It may be prepared from tungsten oxytetrachloride, $WOCl_4$, by the action of anhydrous hydrogen fluoride. Attempts to prepare **tungsten dioxydifluoride,** WO_2F_2, have not been successful, although compounds such as sodium tetrafluotungstate(VI), $Na_2WO_2F_4$, have been prepared.

Tungsten Nitrides.

Although nitrogen does not usually react directly with tungsten, several nitrides are known. **Ditungsten nitride,** W_2N, β, face-centered cubic, has been prepared by the action of ammonia on fine tungsten powder at 700–800°C. If the reaction is allowed to take place at a higher temperature (825–875°C.), however, a second W_2N phase, γ, is formed. This nitride has also been prepared by reacting ammonia with tungsten trioxide. **Tungsten dinitride,** WN_2, density 5 ± 0.5, is a brown-to-black powder which is decomposed by water forming ammonia and tungsten metal. It has been shown to form on bulbs of nitrogen-filled tungsten lamps, and its existence has been confirmed by x-ray analysis. **Ditungsten trinitride,** W_2N_3, is obtained as a black powder by the action of dry ammonia on tungsten hexachloride. Several more complex nitrides have been reported, $4WN_2.W_2(NH_2)_2.2WO_2$, $2WN.W(NH_2)_2$, and $2WN_2.W(NH_2)_2$. See also *Nitrides*.

Tungsten Oxides and Acids.

OXIDES

Tungsten forms three well-defined compounds with oxygen corresponding to valences of +4, +5, and +6. In addition to these three, many other intermediate oxides such as WO, W_2O_3, W_4O_3, and W_5O_{14}, have been reported. The existence of most of these compounds, however, has not been well established and many of them appear to be either solid solutions of two oxides, or mixtures of metallic tungsten and tungsten dioxide.

Tungsten dioxide, WO_2, formula weight 215.92, forms brown, tetragonal crystals, $a = 4.86$ and $c = 2.77$, sp.gr. 12.11. The oxide also exists as a brown, amorphous powder. In this form, it is strongly pyrophoric and is easily oxidized to the trioxide. Tungsten dioxide can be melted under a protective atmosphere, but some disproportionation occurs:

$$3\,WO_2 \rightleftharpoons W + 2\,WO_3$$

Generally, this oxide is obtained as an intermediate product in the hydrogen reduction of the trioxide.

The γ-tungsten oxide, $W_{18}O_{49}$, of Magnéli is probably the same compound. Magnéli also reported a red-violet β-tungsten oxide, $W_{20}O_{58}$ (10).

Ditungsten pentoxide, W_2O_5, commonly known as the blue oxide, may be formed by the partial reduction of the trioxide by hydrogen at 250–300°C. Upon heating, the oxide begins to sublime at 800°C. and is easily reduced by hydrogen to either the dioxide or tungsten metal.

Tungsten trioxide (tungstic oxide), WO_3, formula weight 231.92, is a yellow powder. At room temperature, it is probably monoclinic, but at about 725°C. it transforms to a tetragonal form. The powder has a specific gravity of 7.16 and melts at 1473°C. with some sublimation. This is by far the most important of the tungsten oxides and is generally used as the starting material for the production of tungsten powder. Tungsten trioxide is reduced to metal by carbon above 1050°C. and by hydrogen as low as 650°C. At lower temperatures, mixtures of intermediate oxides are formed. Tungsten trioxide is insoluble in water and in acid solutions but is taken up by strong alkali, forming the tungstate:

$$2\,NaOH + WO_3 \longrightarrow Na_2WO_4 + H_2O$$

When it is heated in a chlorine atmosphere, the oxychloride, WO_2Cl_2, is formed but no reaction occurs with bromine or iodine.

ACIDS AND SALTS

Several hydrates of tungstic oxide, WO_3, have been described in the literature but only three of these have been well defined; tungstic acid, H_2WO_4, its hydrate, approximately $H_2WO_4.H_2O$, and metatungstic acid, $H_8W_{12}O_{40}.xH_2O$. Numerous tungstates, just as with the molybdates but not in all cases analogous to the molybdates, have been reported. Three series have been well characterized: the normal tungstates, M_2WO_4; the metatungstates, $3M_2O.12WO_3.xH_2O$ or $M_6H_2W_{12}O_{40}.xH_2O$; and the paratungstates, $5M_2O.12WO_3.xH_2O$ or $3M_2O.7WO_3.xH_2O$. See also *Heteropoly and isopoly acids*; *Molybdenum compounds.*

Tungstic acid, H_2WO_4, forms an amorphous yellow powder, sp.gr. 5.5. It is insoluble in water or acid solution, but dissolves easily in a strongly alkaline medium. It may be precipitated from a tungstate solution by the action of hot mineral acid. However, the *hydrated acid*, which approaches $H_2WO_4.H_2O$, is formed if the tungstate solution is acidified in the cold. This is a white bulky precipitate which is more soluble in water than the yellow tungstic acid and can be easily converted to the yellow form by boiling in an acid medium.

Tungstic acid will also form a colloidal solution particularly when a sodium tungstate solution is made slightly acid with dilute hydrochloric acid. Upon boiling in concentrated mineral acid, however, the colloid is converted to the yellow insoluble form. Both the yellow and white forms have a great tendency to become colloidal on washing.

Metatungstic acid, $H_8W_{12}O_{40}.xH_2O$, forms small yellow crystals which are readily soluble in water. When heated at 100°C., the anhydrous acid is formed and upon ignition yellow tungstic oxide, WO_3.

Tungstates. The yellow tungstic acid, H_2WO_4, and the white, hydrous compound, $H_2WO_4.H_2O$, form the same series of salts, the **normal tungstates** or **monotungstates** having the general formula $M_2WO_4.4H_2O$. Except for tungstates of the alkali metals and magnesium, these salts are generally sparingly soluble in water.

The action of hot, mineral acids (except phosphoric) decomposes them, precipitating the yellow tungstic acid. The insoluble tungstates can be obtained by adding a solution of sodium tungstate to a solution of the appropriate salt. This usually forms the hydrated salt. The anhydrous tungstates may be prepared by fusing the proper amount of tungstic oxide with the appropriate oxide:

$$CuO + WO_3 \longrightarrow CuWO_4$$

Some general properties of these insoluble tungstates are listed in Table I.

Normal *ammonium tungstate*, $(NH_4)_2WO_4$, cannot be obtained from an aqueous solution since ammonia is evolved when such a solution is concentrated. However, this salt may be obtained by adding hydrated tungstic acid to liquid ammonia.

Sodium tungstate, Na_2WO_4, may be obtained anhydrous by fusing tungstic oxide, WO_3, in the proper proportions with either sodium hydroxide or sodium carbonate:

$$WO_3 + 2\,NaOH \longrightarrow Na_2WO_4 + H_2O$$

$$WO_3 + Na_2CO_3 \longrightarrow Na_2WO_4 + CO_2$$

When it is crystallized from solution, the dihydrate, $Na_2WO_4.2H_2O$, is generally obtained; the decahydrate, $Na_2WO_4.10H_2O$, is formed below 6°C. The density of aqueous solutions of sodium tungstate at 20°C. and the solubility in water of $Na_2WO_4.2H_2O$ are given below:

Concn., g./100 g. soln.	10	20	30	40
d_4^{20}	1.0944	1.2076	1.3444	1.5156

Temp., °C.	20	40	60	80	100
Soly., g./100 g. H_2O	82.2	86.8	93.4	100.9	109.5

TABLE I. Properties of Insoluble Tungstates.

Compound	Color, m.p., crystal structure	Sp.gr.	Solubility
$BaWO_4$	Colorless, tetragonal, a = 5.64, c = 12.70	5.04	Very slightly soluble in H_2O
$CdWO_4$	Yellow rhombic	—	Soluble in NH_4OH; very slightly soluble in H_2O
$CaWO_4$	White, tetragonal, a = 5.24, c = 11.38, n_D^{20} 1.9200	6.06	Slightly soluble in H_2O; insoluble in acids
$Ce_2(WO_4)_3$	Yellow monoclinic, a = 11.51, b = 11.72, c = 7.82, β = 109° 48′, m.p. 1089°C.	6.77	Insoluble in H_2O and acids
$PbWO_4$	Colorless, tetragonal, a = 5.44, c = 12.01, m.p. 1123°C.	8.16	—
$K_2WO_4.2H_2O$	Monoclinic	3.113	Soluble in H_2O; insoluble in alcohol
Ag_2WO_4	Pale yellow	—	Slightly soluble in H_2O; soluble in KCN, NH_4OH
Na_2WO_4	White rhombic, m.p. = 692°C.	4.179	Soluble in H_2O
$Na_2WO_4.2H_2O$	White rhombic; loses $2H_2O$ at 100°C.	3.245	Soluble in H_2O
$SrWO_4$	White, tetragonal, a = 5.40, c = 11.90	6.184	Slightly soluble in H_2O

Metatungstates, $3M_2O.12WO_3.xH_2O$ or $M_6H_2W_{12}O_{40}.xH_2O$, were formerly formulated as $M_2O.4WO_3.xH_2O$ or $M_2W_4O_{13}.xH_2O$ and sometimes called tetratungstates. They are isomorphous with the 12-heteropoly acids such as phosphotungstic and silicotungstic acids (see below). Except for the lead and mercurous salts, most of the metatungstates are soluble in water. They are formed by dissolving tungstic acid in sodium tungstate or by controlled hydrolysis of solutions of sodium tungstate under certain conditions (3).

Paratungstates in the crystalline form are now considered to have the general formula $5M_2O.12WO_3.xH_2O$ or $M_{10}W_{12}O_{41}.xH_2O$, although a few may be better represented by $3M_2O.7WO_3.xH_2O$ or $M_6W_7O_{24}.xH_2O$. They are not isomorphous with the paramolybdates, $M_6Mo_7O_{24}.xH_2O$. In solution the structure of the anion varies with the pH (3). There are some indications that the free paratungstic acid may be present when dilute solutions of barium paratungstate, $5BaO.12WO_3.27H_2O$, and sulfuric acid are mixed, although all attempts to concentrate this solution produce normal tungstic acid instead.

Generally, the paratungstates are crystallized from slightly acid solutions. The sodium salt, $5Na_2O.12WO_3.xH_2O$, may be prepared by saturating a sodium carbonate or sodium hydroxide solution with tungstic oxide, or by nearly neutralizing a boiling solution of sodium tungstate, Na_2WO_4, with hydrochloric acid. A similar method is used to prepare potassium paratungstate.

By far the most important salt in this series is *ammonium paratungstate,* reported to be $5(NH_4)_2O.12WO_3.11H_2O$, which forms fine white needles when crystallized slowly at room temperature from an ammoniacal solution of ammonium tungstate. Rapid crystallization, however, produces transparent, laminated plates. Some dehydration occurs during prolonged boiling, converting the salt to $5(NH_4)_2O.12WO_3.5H_2O$. This second form may also be formed directly by crystallizing from a boiling solution. Both forms are insoluble in water and can be decomposed by either acid or alkali. Upon heating the dried salt in air, ammonia is given off at about 60°C. and dehydration occurs at about 100°C. Reduction to metal occurs by heating in a hydrogen atmosphere. Ammonium paratungstate plays an important role in the commercial process for winning tungsten from its ore (see p. 358).

Many **higher tungstates** have been described in the literature, although often they are not well established. Mention may be made of $2(NH_4)_2O.5WO_3.5H_2O$, $Na_2O.5WO_3$, $(NH_4)_2O.6WO_3.4H_2O$, $Na_2O.6WO_3.15H_2O$, and $Na_2O.8WO_3$.

Peroxytungstic acid, $H_2WO_5.H_2O$ or $WO_3.H_2O_2.H_2O$, is a deep orange amorphous compound obtained by treating tungsten trioxide with a solution of hydrogen peroxide. **Peroxyditungstic acid,** $H_2W_2O_8.2H_2O$ or $2WO_3.H_2O_2.2H_2O$ is also known, but is unstable and decomposes at about 35°C. Salts of these acids similar to the peroxymolybdates (see Vol. **9,** p. 207) have been described in the literature.

Heteropoly acids of tungsten have been described with phosphorus, arsenic, vanadium, and silicon as the central atom. Although the investigation of these compounds is not as yet complete, the existence of many of these has been established. Heteropoly acids of tungsten and phosphorus having $P_2O_5:WO_3$ ratios of 1 to 24, 21, 20, and 18 have been established. The name *phosphotungstic acid,* however, unless otherwise stated, generally refers to the 12-acid, phospho-12-tungstic acid (12-tungstophosphoric acid), $H_3PO_4.12WO_3.xH_2O$ or $H_3PW_{12}O_{40}.xH_2O$, which forms greenish-yellow crystals and may be obtained by evaporating a solution containing the proper concentration of phosphoric and metatungstic acids. *Silicotungstic acid* (12-tungsto-

silicic acid), $SiO_2.12WO_3.26H_2O$ or $H_4SiW_{12}O_{40}.xH_2O$, forms very pale yellow rhombic crystals which are quite soluble in water, alcohol, and ether. The salts of this acid, except mercurous silicotungstate, are mostly soluble. Several other acids having a different ratio of SiO_2 to WO_3 have been described together with their salts. *Borotungstic acids* containing one mole of B_2O_3 combined with 9, 24, or 28 moles of WO_3 have been described in the literature. The principal acid in this series is the *12-tungstoboric acid*, $H_5BW_{12}O_{40}.xH_2O$, which forms a well-defined series of salts having the general formula $M_5BW_{12}O_{40}.xH_2O$. These have been obtained by neutralizing the acid with either a metal hydroxide or carbonate. In general, these salts are very similar to the silicotungstates but they are less easily crystallized and less stable. See also *Heteropoly and isopoly acids.*

Tungsten bronzes are a series of compounds having the general formula M_xWO_3 where x is less than one. These compounds are colored, ranging from golden-yellow to bluish-black depending upon the ratio of metallic cations to WO_3. In this series, the cation is generally an alkali metal such as sodium, potassium, or lithium, although alkali–alkaline earth tungsten bronzes have been described. The sodium tungsten bronzes are crystalline with a specific gravity ranging from 6.5 to 7.5 and insoluble in water, acids, and alkali. In general, these bronzes form cubic or tetragonal crystals, the lattice constants increasing with sodium concentration. These compounds are excellent electrical conductors, with properties very close to those of the alkali metals. When made the anode in electrolysis, they do not conduct (after an initial momentary surge), but they will conduct as cathodes (except in potassium permanganate solution). This has been attributed to the formation of a nonconductive film of yellow tungstic oxide, which is reduced when the polarity is reversed to a lower tungsten oxide which is conductive. Some of the electrical properties of $Na_{0.66}WO_3$ are as follows:

Resistivity $= 1.9 \pm 0.02 \times 10^{-4}$ ohm-cm. at 0°C.
Hall coef. $= -5.1 \pm 0.2 \times 10^{-4}$ cm./coulomb at 20°C.
Paramagnetic susceptibility $x = 0.53 \times 10^{-6}$

The compounds may be prepared by fusing a mixture of the normal tungstate (anhydrous) with tungstic oxide and free tungsten.

Tungsten Phosphides.

Tungsten subphosphide, W_2P or W_4P_2, dark gray, tetragonal, $a = 6.18$ and $c = 6.78$, sp.gr. 5.21, can be prepared by heating a mixture of phosphoric and tungstic oxides in a carbon crucible. It is insoluble in acid and oxidizes when heated in air.

Tungsten monophosphide, WP, is a gray powder, sp.gr. 12.3. It is insoluble in water, hydrochloric acid, and alkaline mediums, but is attacked by a nitric acid–hydrofluoric acid mixture. The monophosphide is very similar to the diphosphide in its behavior toward the halogens and oxygen.

Tritungsten tetraphosphide, W_3P_4, is a crystalline powder obtained by the action of phosphorus upon metallic tungsten at red heat.

Tungsten diphosphide, WP_2, is a black crystalline powder, sp.gr. 9.17, prepared by heating tungsten hexachloride with dry phosphine at 450–500°C:

$$WCl_6 + 2\,PH_3 \longrightarrow WP_2 + 6\,HCl$$

The phosphide is insoluble in water, acids, alcohol, and ether. It may be decomposed by a nitric acid–hydrofluoric acid mixture, however. It is also attacked by the halogens upon heating.

Tungsten Silicides.

Ditungsten trisilicide (tungsten sesquisilicide), W_2Si_3, is gray, sp.gr. 10.9, insoluble in water, acid, or alkaline solutions. It is readily attacked by a mixture of nitric acid and hydrofluoric acids and by fused alkali metal hydroxides and carbonates.

Tungsten disilicide, WSi_2, forms tetragonal crystals with $a = 3.212$ and $c = 7.880$. The compound is attacked by fluorine, chlorine, fused alkalies, and nitric acid–hydrofluoric acid mixtures. It is insoluble in water.

Tungsten trisilicide, WSi_3, is very similar chemically to the disilicide.

Tungsten Sulfides.

Tungsten disulfide, WS_2, is found in nature as the mineral tungstenite, which forms a soft, lustrous, dark gray crystalline powder, sp.gr. 7.5 (10°C.). The mineral as it occurs in nature is characterized by its earthy or foliated appearance. The sulfide is oxidized by air at elevated temperatures, producing tungstic oxide. It is also attacked by the halogens forming the respective halides, and may be reduced to metallic tungsten by hydrogen at about 800–900°C. At 1250°C., tungsten disulfide is decomposed without melting. The compound is insoluble in water but readily attacked by a mixture of nitric and hydrofluoric acids, or fused alkali. It may be prepared by heating tungsten hexachloride in hydrogen sulfide at 375–550°C. or by strongly heating the two elements.

Tungsten trisulfide, WS_3, is a black powder, slightly soluble in cold water, readily forming a colloidal solution in hot water. It is generally prepared by treating an alkali thiotungstate with excess acid. The compound is easily soluble in alkali hydroxides, carbonates, and sulfides.

Tungsten also forms a series of **thiotungstates** corresponding to the normal salts but with one, two, three, or all of the oxygen atoms replaced by sulfur. The potassium thiotungstates have the following formulas: $K_2WO_3S.H_2O$, $K_2WO_2S_2$, $K_2WOS_3.H_2O$, K_2WS_4, and similar compounds of other metals are known.

These compounds are formed when solutions of the alkali or alkaline earth tungstates are saturated with hydrogen sulfide. These salts vary in color from pale yellow to yellowish brown and in general crystallize well. Upon acidifying a solution of these salts, however, tungsten trisulfide is obtained. *Potassium tetrathiotungstate*, K_2WS_4, forms yellow rhombic crystals which are quite soluble in water. *Ammonium tetrathiotungstate*, $(NH_4)_2WS_4$, forms bright orange crystals having a metallic iridescence which are stable in dry air and are quite soluble in water. Solutions of this salt, however, decompose upon standing in air. It is generally prepared by treating a solution of tungstic acid with excess ammonia and saturating with hydrogen sulfide.

Uses

With the exception of tungsten carbide, WC (see p. 362), there are few applications of major importance for tungsten compounds. Two tungsten compounds, tungsten oxide and sodium tungstate, are available commercially. Current prices (1955) for each are:

Tungstic oxide, over 1000-lb. quantities	$2.25/lb.
Sodium tungstate, technical, 400-lb. and 25-lb. drum	2.54–2.76/lb.

Both of these compounds play an important role in the metallurgy of tungsten.

Calcium and barium tungstate are used in x-ray photography for the manufacture of intensifying and phosphorescent screens. A 10% lead sulfate solid solution with these salts produces emission peaks of 4300 A. and 4700 A., respectively. Magnesium tungstate, $MgWO_4$ or Mg_2WO_5, is also employed as a blue-emitting phosphor. See *Luminescent materials*; *Radiography, industrial.*

Minor applications of tungsten compounds include the use of sodium tungstate to flameproof cloth (see *Fire-resistant textiles*), the use of phosphotungstic acid in the preparation of pigments for the printing ink industry, and analytical reagents.

There is some mention in the literature of the use of tungsten oxide, WO_3, in the glass and ceramic industry as a yellow coloring agent. Its use, however, is not believed to be standard practice.

Tungsten compounds have been tested as tanning agents, and found to form a very beautiful and pliable white leather.

Many patents have been granted based upon the ability of tungsten and tungsten oxides to catalyze the hydrogenation and cracking of hydrocarbons. Information, however, is not available on whether these are being used in any present-day commercial process.

Bibliography

(1) Arkel, A. E. van, *Reine Metalle*, Springer, Berlin, 1939 (photo-lithoprinted, Edwards Bros., Ann Arbor, Mich., 1943).
(2) Brimm, E. O., Brawley, J. C., Lorenz, J. H., and Jellinik, M. H., *J. Am. Chem. Soc.*, **73**, 5427–33 (1951).
(3) Emeléus, H. J., and Anderson, J. S., *Modern Aspects of Inorganic Chemistry*, 2nd ed., Van Nostrand, N.Y., 1952, pp. 216–19, 496–501.
(4) Ephraim, F., *Inorganic Chemistry*, 5th English ed., Interscience, N.Y.-London, 1948, pp. 323–57.
(5) Gmelin, 8th ed., 1933, System-Nummer 54, p. 397.
(6) Hopkins, B. S., *Chapters in the Chemistry of the Less Familiar Metals*, 1940, Stipes Pub. Co., Champaign, Ill., Ch. 17, pp. 1–29.
(7) International Critical Tables, McGraw-Hill, N.Y.,
(8) Lander, J. J., and Germer, L. H., *Metals Technol.*, **14**, No. 6, Tech. Pub. 2259 (1947).
(9) Li, K. C., and Wong, C. Y., *Tungsten*, 2nd ed., Reinhold, N.Y., 1947.
(10) Magnéli, A., *Arkiv. Kemi*, **1**, 223 (1949); **1**, 513 (1950).
(11) Mellor, 1931, Vol. XI, pp. 741–874.
(12) Priest, H. F., and Schumb, W. C., *J. Am. Chem. Soc.*, **70**, 3378–79 (1948).
(13) Schwarzkopf, P., and Kieffer, R., *Refractory Hard Metals*, Macmillan, 1953.
(14) Sidgwick, N. V., 1950, Vol. II, pp. 1028–68.
(15) Wyckoff, R. W. G., *Crystal Structures*, Interscience, N.Y.-London, 1948.
(16) U.S. Pat. 2,387,872 (Oct. 30, 1945), M. E. Bell (to Westinghouse Electric Co.).
(17) U.S. Pat. 2,554,194 (May 22, 1951), D. T. Hurd (to General Electric Co.).

BERNARD KOPELMAN

TURBIDIMETRY AND NEPHELOMETRY

Turbidimetry and nephelometry are used to study the intensity of light scattered from inhomogeneities in a wide variety of systems. The study is called turbidimetry if the quantity measured is the decrease of intensity of the incident light beam caused by scattering in the system, or nephelometry if the intensity of scattered light is measured directly. The systems that have been studied cover the wide range from the weak scattering produced by very small inhomogeneities found in gases, pure liquids, and imperfect crystals, through the range of moderate scattering intensities observed with solutions of large molecules such as natural and synthetic polymeric materials, to the strong intensities observed with suspensions of large particles.

General Principles

The theory of scattering by these systems is well established and allows the calculation of the number of scattering elements, as well as their maximum dimension in certain systems. Such calculations are difficult in other cases, especially for large particles, either because the mathematical theory becomes complex, or because the shape and uniformity of the particles must be known. A large number of applications involve only relative measurements of the scattering, and these permit an estimate of the relative number of scattering particles present, if the particle size is the same for the unknown and the standard samples. Since about 1945, a most fruitful application of light-scattering has been the determination of absolute molecular weights and dimensions of polymers and other large molecules in solution.

True light-scattering causes no loss in the total radiation of light at the wave length used; the sum of the energy after passage through a turbid sample plus the total of all scattered light energies equals that of the incident beam. This is in contrast to light absorption and fluorescence, in which light is converted to energy of longer wave length.

The *coefficient of turbidity*, τ, is related to the total light intensity lost from an incident beam as the result of scattering by the equation:

$$I = I_0 e^{-\tau l} \tag{1}$$

where I_0 is the incident intensity and I is the intensity remaining after passage through the length, l, of the sample. This equation neglects losses by reflection from cell surfaces (which may be corrected by use of a comparison cell), and it assumes that no loss of intensity occurs by absorption of light. Loss by absorption follows a similar law in which the extinction coefficient replaces the turbidity coefficient (see *Colorimetry and fluorimetry*).

Equation (1) shows that the turbidity coefficient may be obtained by measurements of the transmittance, I/I_0, of a nonabsorbing sample, but this method is practically restricted to suspensions where cloudiness is easily visible ($\tau > 10^{-2}$) in order to obtain fair precision. For less turbid samples, it is frequently desirable to measure the scattered light directly, and this may be done with precision for solutions whose turbidity coefficient is 10^{-5} or even less. In most applications, the scattered intensity is then used directly, but τ may be calculated if the scattering follows a known angular intensity pattern. Particles whose dimension is less than one-twentieth the wave length of light obey the Rayleigh equation (see p. 374), and in this case the total scattered light can be calculated by measuring i_{90}, the intensity scattered at an angle of 90°

to the incident beam relative to the intensity of the incident beam, according to equation (2):

$$\tau = \frac{2\pi r^2}{I_0} \int_0^\pi i_\theta \sin\theta \, d\theta = \frac{16}{3} \pi r^2 \frac{i_{90}}{I_0} \tag{2}$$

in which r is the distance from the scattering source to the receiver.

Theory of Scattering

Particles Smaller than 0.05 λ. The description by Tyndall in 1869 of the effect of particle size of droplets dispersed in air on the color and polarization of light which they scattered, was soon followed in 1871 by Rayleigh's development of a theory to explain on a quantitative basis the scattering from disperse systems of small dielectric particles. The wave theory of light states that during the passage of light through matter, all particles are forced into vibration and radiate light in all directions. If the medium is perfectly homogeneous, destructive interference between the waves produced by neighboring particles cancels the light radiation in all directions except that of the incident beam. Any inhomogeneity of the medium makes this cancellation imperfect, so that some scattered light is produced. Inhomogeneities produced by thermal movement of molecules lead to the very slight scattering of single-component gas, liquid, or solid systems. Mixtures of components having different refractive indexes scatter with greater intensity, and the equation developed by Rayleigh expresses the relation between the incident intensity I_0 of light of wave length λ, and the intensity i_θ, of light scattered at angle θ, and the distance r from the particles to the point of measurement, in terms of the number N of particles, each of volume V. The ratio n'/n is the refractive index of the solution divided by that of the solvent. The Rayleigh equation is:

$$\frac{i_\theta}{I_0} = \left(\frac{n'}{n} - 1\right)^2 \frac{NV^2}{\lambda^4 r^2} (1 + \cos^2\theta) \tag{3}$$

Equation (3) indicates that the intensity scattered by a given weight of material, divided into particles of uniform size, will be proportional to the square of the particle volume, and thus to the sixth power of the radius. The intensity is also highly dependent on the wave length of the light, being about nine times as intense for blue light as for red light. A beam of white light therefore becomes progressively redder as it passes through a sample of such particles, while the scattered light is much bluer than the incident light. This explains the blue color of the sky and the red color of sunsets resulting from light passing through thick layers of scattering particles. The polarization of the scattered light is expressed by the term $(1 + \cos^2\theta)$ which includes constant intensity of light whose plane of polarization is perpendicular to the plane formed by the incident and scattered light rays, and a variable term, dependent on the angle of observation, for light polarized parallel to the plane. The light scattered at 90° is expected to be polarized perpendicular to the plane.

The Rayleigh equation is strictly applicable to isotropic, dielectric particles whose maximum dimension is less than one-twentieth the wave length of light used, and at concentrations where no interaction occurs between particles. Most applications are made under conditions which depart from some of these requirements, and several methods have been devised for overcoming the resulting difficulties. The modifications of the theory that have permitted molecular-weight and dimension measurements for polymer solutions were made by Debye. Further refinements have been added by a large number of contributors. Thorough reviews of these developments have been presented by Oster (5), West (6), and Doty and Edsall (2). Essentially the nonideal behavior, which is normally found even in dilute (about 1%) solutions of polymers, was treated by Debye in a way similar to that used in osmotic pressure. The result was an equation applicable to particles of maximum dimension less than one-twentieth the wave length of light, and which permits the calculation of their molecular weight, M, from measurements of the turbidity coefficient at a series of weight concentrations, c. This equation is:

$$\frac{Hc}{\tau} = \frac{1}{M} + \frac{2Bc}{RT} \tag{4}$$

in which R is the gas constant, T, the absolute temperature, and H is a constant whose value may be obtained from the specific refractive index gradient, $(n' - n)/c$, and other quantities in the equation:

$$H = \frac{32}{3} \frac{\pi^2 n^2}{N\lambda^4} \left(\frac{n' - n}{c} \right)^2 \tag{5}$$

in which N is Avogadro's number. These equations have been tested by measurements of a variety of large molecules whose molecular weights are well established, and the agreement is very satisfactory.

Particles 0.1–0.8λ. When a dimension of the scattering particle exceeds about one-twentieth the wave length of light, Rayleigh's law of scattering is not exactly obeyed, as shown by an unsymmetrical angular distribution of scattered light, and the decrease of the wave length exponent in the intensity relation. These effects are the result of destructive interference of light scattered from different parts of the particle which leads to smaller intensity in the backward than the forward direction. This unsymmetrical intensity distribution is often expressed by the *dissymmetry coefficient*, z, which is the ratio of intensities at two angles symmetrical about the perpendicular to the incident beam.

Debye simplified the problem of calculating the angular distribution of scattering for these larger particles by assuming a negligible difference of refractive index between the particles and the solvent, and so was able to obtain rather simple equations for the complete intensity distributions for spheres, rods, and randomly kinked chains. These equations have been applied to correct the smaller intensity of scattering to that which would have occurred in the absence of interference, and two methods have been much used for accomplishing this—one utilizing the dissymmetry coefficient mentioned above, and the other a grid method of plotting data at various angles and concentrations (8). By these means, the molecular weight may be calculated by the equation developed for small particles, and modified only by using the corrected turbidity coefficient.

In the range of particle sizes where the dissymmetry coefficient is 1.1–3, an average maximum dimension of the scattering particles may be obtained from the dissymmetry of scattering, provided the shape of the molecules is known. The dimension can be calculated without assumption of particle shape if the grid method, previously mentioned, is used.

When the particles studied are not uniform in size, as is usual for synthetic polymers and many derived natural polymers, then the molecular weight which is obtained from light-scattering is usually the weight-average value, which is always larger for such polydisperse systems than the number-average value obtained by methods involving osmotic pressure or other colligative properties.

Particles Larger than 0.8λ. The theory of scattering by large particles is so complex that only one type of system has been developed sufficiently to allow calculation of particle sizes. In 1908 Mie solved the problem for uniform spherical particles of known size and index of refraction, and the expected effects have recently been confirmed and thoroughly studied by LaMer and coworkers (4). As the particle radius increases from the Rayleigh scattering region to about 0.1 micron, the angular intensity pattern is progressively distorted as interference decreases the scattering, particularly in the backward direction; while at the same time the total scattered intensity per particle increases rapidly. When the diameter reaches about 1 micron, depending on the ratio of refractive indexes, very pronounced intensity maxima are found at a series of angles when examined with monochromatic light. If white light is used, spectra, called *higher-order Tyndall spectra*, may be observed with the eye at a series of positions; these represent the positions of the maxima which occur at different angles, dependent on the wave length. The larger the particle, the greater the number of maxima, until for sulfur particles of 2 microns diameter, ten maxima for red light have been observed in half the total light envelope. Several methods based on the position and number of these maxima have been developed for determining particle sizes of the uniform particles found in some smokes, aerosols, and liquid suspensions. However, if the particles are not very nearly uniform in size, the maxima and colored bands become very poorly defined, so that these methods cannot be used.

Another method applicable to spherical particles in the size range from about 0.06 to 0.2 micron diameter depends on the *wave length exponent of scattering intensities*. As particle size increases from the range of Rayleigh scattering to about 0.2 micron diameter, the Mie equations predict that the total intensity of scattering is proportional to powers of the wave length systematically decreasing from four to two, but invariable for still larger particles. Heller, Klevens, and Oppenheimer (3) employed this principle for the determination of dimensions of polystyrene latex particles suspended in water, and studied the increase of particle size during emulsion polymerization. The exponent

may be calculated from the equations of Mie for uniform size particles, but it is usual to construct calibration curves for particles whose size is known from other methods. The logarithm of the turbidity coefficient, calculated from transmission measurements, is plotted against the logarithm of the series of wave lengths used to give a straight line in the absence of absorption. The slope of this line gives the wave length exponent and therefore the particle size.

Experimental Methods

Transmission Instruments—Turbidimeters. The transmission method (turbidimetry) is limited to samples that show obvious turbidity, since a considerable decrease of the incident intensity is necessary to yield precise results; for example, a 1 cm. thickness of solution whose turbidity coefficient is 10^{-2} has a transmittance of 98%. Many of the analytical applications of light-scattering involve quite turbid solutions for which transmission measurements are very useful.

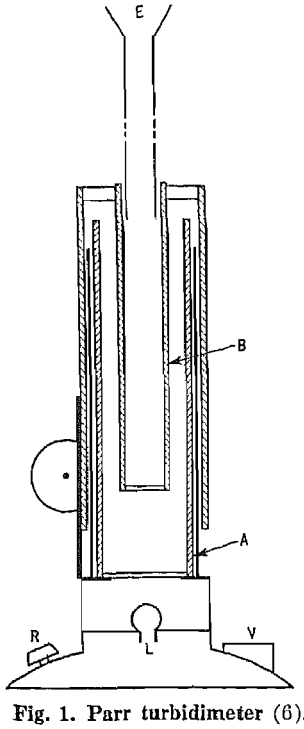


Fig. 1. Parr turbidimeter (6). *A*, Fixed tube; *B*, plunger; *E*, eye position; *L*, lamp; *V*, voltmeter; *R*, rheostat.

The simplest form of transmission instrument is represented by *extinction turbidimeters* of the Parr (see Fig. 1) or Jackson types in which the length of a column of turbid solution is increased until a light source viewed through the column just disappears. The reciprocal of the required column length is, under selected conditions, proportional to the turbidity, although usually a calibration curve is constructed for known quantities of particles prepared under the same conditions. Curvature in such calibration curves results either from changes in the size distribution of the particles or from the effect of multiple scattering, which causes the apparent turbidity coefficient to become smaller as the sample length is increased. Comparative measurements of turbidity may also be made with *colorimeters of the Duboscq type* (see Vol. **4,** p. 270) operated as in colorimetry. Again the relative turbidity is approximately inversely proportional to the ratio of column lengths.

Photoelectric transmission photometers of various types are frequently used for turbidity measurements. Filter photometers or other instruments that use light of relatively broad wave length range are quite suitable for very large particle sizes, especially for comparative measurements, where a standard of closely similar form is used. The narrower wave length region obtainable by the use of prism or grating spectrophotometers is particularly useful for smaller particle sizes (below 0.2 micron diameter) where the intensity of scattering is so dependent on wave length, or where absolute measurements are required. *Spectrophotometers* also permit the use of the wave length – exponent method, already referred to, since the transmittance may be measured at a large number of wave lengths.

Scattered Intensity Instruments—Nephelometers. Greater precision and sensitivity may be obtained with instruments which measure the intensity of scattered light (nephelometers), because this is a direct rather than a difference method. For ex-

ample, several instruments are available that will detect scattering from solutions whose turbidity coefficient is 10^{-6}.

Visual nephelometers include the Duboscq colorimeter, modified to give lateral illumination of two similar cells with clear walls and opaque bottoms. The depth of scattering liquid is varied until the two halves of a field match in brightness. One half of the field is illuminated by scattered light from the sample cell and the other by light from a standard of known turbidity or concentration. The Hellige instrument requires only occasional use of standards, since it compares the intensity of scattered light with the reduced incident intensity. Other instruments suited for visual measurements of small intensities of scattering have been described (7), but are not available commercially.

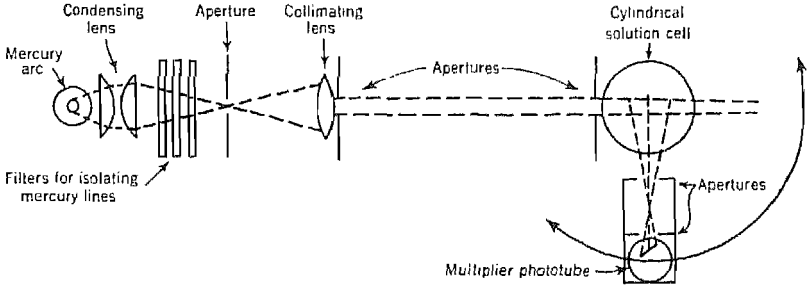


Fig. 2. Photometer for angular scattering intensities.

Photoelectric nephelometers of moderate sensitivity may consist of commercial filter photometers with attachments to measure scattered intensity. Fluorimeter attachments such as those for the Nefluoro-photometer (Fisher Scientific Co.), or the Lumetron Colorimeter (Photovolt Corp.) may be satisfactory, although they accept light from a wide range of angles.

Two instruments for the high precision and sensitivity required in the measurement of polymer molecular weights are the Phoenix (Phoenix Instrument Co.) and the Aminco (American Instrument Co.) photometers. These are provided with filtered mercury arc sources which provide high intensity illumination in a narrow wave length range, both being necessary where the scattering is weak and strongly dependent on the wave length. They also permit measurements at a series of well-defined angles by rotation of the phototubes about 6-sided or cylindrical cells. Figure 2 is a schematic drawing of this type of instrument. The scattered intensities are either compared to that from a standard of known scattering power, or to the incident light intensity, after suitable reduction of intensity with calibrated filters. In either case, measurements of absolute scattering intensities are possible with good precision. The high sensitivity obtained with photomultiplier tubes combined with amplifiers permits the determination of the scattering power of pure liquids, including water.

Preparation of Samples. Considerable care is necessary in preparing samples for all light-scattering measurements. Greatest errors in measurements of small intensities are caused by suspended impurities, such as dust, which scatter light very strongly, but these impurities are inconsequential in measurements with large particles. Variations of particle size and stability greatly affect the results of scattering by large particles.

Solutions of small particles can frequently be freed of large inclusions by filtration, ultrafiltration, or centrifugation. The most suitable techniques vary with the sample and solvent used.

The production of stable suspensions of moderate—and large—size particles is most important for exact and reproducible results, since the intensity of scattering depends so much on the particle size. For analytical purposes where a suspension of a precipitate is formed by chemical reaction, it is best to prepare a calibration curve obtained with known amounts of the constituent precipitated under the same conditions as the unknown. This is because the particle size and shape of precipitates is greatly affected by temperature, pH, salt concentration, agitation, and rate of addition of the precipitant. The precipitate should be finely divided and neither fibrous nor flocculent. Greatest stability is obtained in some cases in the presence of small amounts of acid or alkali, or by the addition of gelatin, starch, gum arabic, egg albumin, or wetting agents which adsorb on particle surfaces and prevent their agglomeration, usually by repulsion of like-charged particles. In general, large salt concentrations, agitation, and heating favor the agglomeration of suspensions and are to be avoided. The development of procedures for the determination of a constituent by precipitation and measurement of turbidity requires tests of the reproducibility of scattering from known amounts over the range to be analyzed, and of the stability over a time period sufficient to complete measurements for a series of samples. It is also desirable to operate in such a concentration range that the turbidity or intensity of scattering produced is approximately proportional to the concentration of the constituent, and not curved excessively by multiple scattering.

Applications

Comparison of Methods for Particle-Size Measurement. Figure 3 shows a range of particle sizes that can be measured by light-scattering techniques. See also *Size measurement.* The range of the methods listed is only approximate, and the lower

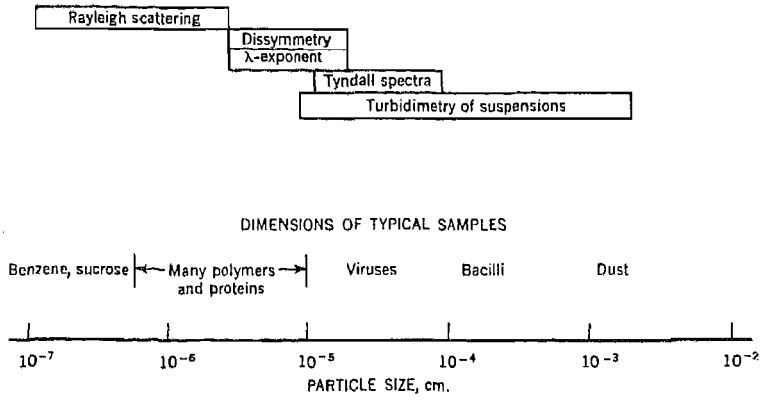


Fig. 3. Range of particle sizes accessible by light-scattering methods.

limit depends on favorable conditions, such as high refractive index compared to the medium, absence of spectral absorption bands, and the most sensitive measuring devices. Nephelometric methods are seen to be of especially great value in the small particle range where the other successful methods require complex and expensive

installations. The applications to large particles are chiefly for analytical and particle size distribution measurements.

Molecular-Weight Measurements. Molecular weights of particles in solution are determined by measurements of scattering intensities at a series of concentrations, and extrapolation of these data to zero concentration using equation (4). The absolute molecular weights are then calculated when the constant H (equation (5)) is evaluated by refractive index measurements.

Results have been reported for molecules as small as sucrose (342) and as large as tobacco mosaic virus (4×10^7), but most precise measurements probably are made above molecular weights of 2×10^4, where the scattering is strong. Thus, this method overlaps the best range for osmotic pressure measurements and extends to values inaccessible by that method.

Dimension measurements are only possible for particles with one dimension at least 500 A., which usually requires molecular weights greater than 2×10^5.

Both the dimension and molecular-weight results of light-scattering methods are in good agreement with values obtained by sedimentation, osmotic pressure, and electron microscope measurements. The most reliable comparisons have been made with globular proteins of uniform particle size. Here the agreement of the results is within about 5% for most substances.

Analytical Chemistry. Probably the most frequently used analytical method involving light-scattering techniques is for the determination of sulfur in a wide variety of materials such as water, food, and coal. The sulfur is converted to sulfate ion and the hot solution is treated with barium chloride in the presence of low concentrations of salt and hydrochloric acid, and sometimes with the addition of a protective colloid. Under these conditions barium sulfate precipitates as a fairly stable suspension of very finely divided particles. The method is most useful where the sulfur content ranges from a few parts per million to about 100 p.p.m.

Table I (7) illustrates the usual concentration ranges in which nephelometric methods are useful. In addition to the methods mentioned, reference (7) outlines methods for a large number of organic compounds including fats and oils, fatty acids, purines, and proteins of various types. The reproducibility claimed for these methods ranges from 1 to 5% on samples between 0.2 microgram and 1 milligram, which places these among the most sensitive of analytical methods.

TABLE I. Typical Analytical Applications of Nephelometry.

Constituent	Precipitate	Lower limit, mg./100 ml.	Upper limit, mg./100 ml.
S	$BaSO_4$	0.08	0.8
Cl	AgCl	0.014	1.0
NH_3	$HgNH_2Cl$	0.0006	0.1
As	Molybdenum complex	0.006	0.7
Ca	Calcium stearate	0.0002	—
P	Molybdenum complex	0.0003	0.05

Nephelometric methods are also used in precipitation titrations to detect the first appearance of a precipitate. The precipitant is titrated directly into the stirred solution in the cell of a nephelometer, or sometimes a turbidimeter, until a perceptible deflection of the current-measuring instrument or visible cloudiness occurs.

Particle-Size Distribution. Although light-scattering methods are usually unable to indicate the distribution of particle size, they have often been employed in the analysis of particles separated into fractions by other means, such as sedimentation or elutriation. In one sedimentation method, samples are removed from different sections of a liquid column after partial sedimentation has separated the broad distribution of particles. In a different modification, the turbidity of a solution is measured as particles progressively sediment past the light beam. Both these methods are highly dependent on knowledge of the scattering power of particles of different diameters. This, in turn, is considerably influenced by particle shape, so that calibration curves are required.

If the intensity of scattering for different particle sizes is calculated on the basis of constant weight of material, it is seen that the intensity increases rapidly with dimension ($\sim r^3$) in the Rayleigh scattering range, but since large particles are known to scatter in proportion to their cross-sectional area, it is clear that their scattering intensity will decrease ($\sim 1/r$) as particle size increases in this range. The scattering power of suspensions in a broad range of dimensions has been studied by Andreason (1) who showed that a maximum in the turbidity coefficient divided by weight concentration of particles occurred at diameters between 0.5 and 0.9 micron, depending on the wave length of light used. This result is close to that calculated from the Mie theory, which expects maximum scattering for a given weight when the particles have diameters about equal to the wave length of light.

Other Applications. The scattering power of large particles is quite important in applications such as the paint industry, where the covering power of pigments and extenders is quite dependent on particle size. Since colorless particles have their greatest scattering power, leading to greatest paint opacity, when the particle diameter is about 0.5 micron which is about equal to the wave length of light, it is desirable to grind pigments to this size. Scattering by colored particles is dependent on the absorption band, but is usually greatest for somewhat smaller particle sizes for absorbers than for nonabsorbers. Scattering of white light is an undesirable characteristic for black or deeply colored particles, and can best be avoided with particles of very small size.

Bibliography

(1) Andreason, A. H. M., in "Symposium on Particle Size Analysis," Supplement to Transactions, Institution of Chemical Engineers, **25**, 4–13 (1947).
(2) Doty, P., and Edsall, J. T., *Advances in Protein Chemistry*, Academic Press, N.Y., 1951, Vol. VI, pp. 35–122.
(3) Heller, W., Klevens, H. B., and Oppenheimer, H. O., *J. Chem. Phys.*, **14**, 566 (1946).
(4) Johnson, I., and LaMer, V. K., *J. Am. Chem. Soc.*, **69**, 1184 (1947).
(5) Oster, G., *Chem. Revs.*, **43**, 319–65 (1948).
(6) West, W., "Colorimetry, Photometric Analysis, Fluorimetry Turbidimetry," in Weissberger, *Physical Methods of Organic Chemistry*, Interscience, N.Y., 1949, Vol. I, Pt. 2.
(7) Yoe, J. H., and Kleinmann, H., *Photometric Chemical Analysis*, Wiley, N.Y., 1929, Vol. II.
(8) Zimm, B. H., *J. Chem. Phys.*, **16**, 1093–1116 (1948).

G. L. BEYER

TURICINE, $C_7H_{13}NO_3$. See *Alkaloids*, Vol. **1**, p. 475.

TURKEY-RED OIL. See *Castor oil*, Vol. **3**, p. 240.

TURMERIC. See *Dyes*, Vol. **5**, p. 352.

TURNBULL BLUE. See "Iron cyanide blues" under *Cyanides*, Vol. **4**, p. 731.

TURPENTINE

Turpentine (spirits of turpentine) is a light, volatile essential oil obtained from resinous exudates or resinous wood associated with living or dead coniferous trees, particularly of the genus *Pinus*, or, more commonly, pines (see also *Resins, natural*). The word "turpentine," as originally used and as still used in pharmacy and in the phrase Venice turpentine (larch turpentine), refers to the whole oleoresinous exudate from the living pine tree. Accordingly, the volatile portion of the "turpentine" separated by distillation was called "spirits of turpentine" and the nonvolatile portion was called rosin (*q.v.*) or colophony. Today the term "spirits" or "oil" is still used in conjunction with the word turpentine, although the term turpentine alone and the shortened form "turps" are popularly used for any distilled turpentine.

In the U.S. an act of Congress, the Naval Stores Act of March 3, 1923, established standard grades of turpentine and other regulatory measures to prevent adulteration and deception of any nature involving turpentine marketing transactions within the United States and its possessions. In *Service and Regulatory Announcements* (2) relative to this act, the standard designations for the four approved types of turpentine commercially available in the U.S. are defined as follows:

Gum spirits of turpentine. The designation "gum spirits of turpentine" shall refer to the kind of spirits of turpentine obtained by distillation of the oleoresin (gum) from living trees, and commonly known prior to the passage of the act as gum spirits, gum turpentine, spirits of turpentine, or oil of turpentine.

Steam-distilled wood turpentine. The designation "steam-distilled wood turpentine" shall refer to the kind of spirits of turpentine obtained by steam distillation from the oleoresinous component of wood, whether in the presence of the wood or after extraction from the wood, and commonly known prior to the passage of the act as wood turpentine, steam-distilled turpentine, steam-distilled wood turpentine, or S. D. wood turpentine.

Destructively distilled wood turpentine. The designation "destructively distilled wood turpentine" shall refer to the kind of spirits of turpentine prepared from the distillate obtained in the destructive distillation (carbonization) of wood, and commonly known prior to the passage of the act as destructively distilled wood turpentine or D. D. wood turpentine.

Sulfate wood turpentine. The designation "sulfate wood turpentine" shall refer to the kind of spirits of turpentine prepared from the condensates that are recovered in the sulfate process of cooking wood pulp, and commonly known as sulfate turpentine or sulfate wood turpentine.

Chemically, turpentine is a mixture of cyclic monoterpene hydrocarbons, $C_{10}H_{16}$, the predominant constituent of most turpentines being α-pinene (see *Terpenes (mono-, cyclic)*). Turpentine is produced in several countries, generally where there are vast tracts of pine.

The largest use throughout the world for turpentine is as a thinner for various types of oleoresin-based paints and varnishes. Of secondary importance is its use as a solvent for waxes and polishes, and as an intermediate in the preparation of synthetic camphor, synthetic pine oil, oil additives, and insecticides. It is also used in the manufacture of synthetic resins.

Naval stores, as applied to the industry today, includes a host of manufactured products having a common derivation from gums or resins associated with living or dead coniferous trees. Modern naval stores products which have a wide range of uses include pine oil, refined turpentines and the pure chemicals comprising them, such as

α-pinene, β-pinene, and dipentene; also refined and modified rosins, and many chemical derivatives of terpenes and the resin acids comprising rosin.

Historically, the term "naval stores" was applied to supplies involved in calking and weather-proofing the timbers and rigging of early sea-going vessels. Few in number, they included tars and pitches crudely processed from resinous wood or gums of pines.

In America, production of naval stores had its origin in the northern colonies and crude products were produced and shipped abroad from this area throughout the 17th century (24). By the 18th century, production of naval stores had shifted southward and centered around North Carolina. At this time very little turpentine was distilled because the whole of the oleoresin collected was sent to England for processing into turpentine and rosin. About the middle of the 18th century, crude stills came into use and an estimated 10,000 barrels of turpentine was being produced annually. Today Georgia produces 75% of the U.S. gum turpentine. Florida and Alabama produce slightly more than 20%, and all the rest of the southern gum-turpentine-producing states account for somewhat less than 10%.

Properties

Composition. The overall chemical compositions of natural and commercial grades of turpentine vary widely, but all grades are composed predominantly of a mixture of isomeric, unsaturated, bicyclic monoterpene hydrocarbons, $C_{10}H_{16}$. The marked differences in turpentines occur in the lesser components. These make up a complex mixture which includes minor amounts of saturated and unsaturated monocyclic terpenes, aromatics, oxygen-containing compounds mostly of terpene origin, and trace amounts of a variety of naturally occurring compounds generally associated with wood resins and plant life. Considering the commonplace origin and commercial importance of turpentine, studies of its composition have been few and only recently have the minor components been systematically identified. More notable of those who have investigated this aspect of turpentine using modern methods of chemical and instrumental analysis are Palkin, Chadwick and Matlack (4,5,23), and Mirov (18) in the U.S., and Dupont in France (6).

The variation in types and concentrations of the major, minor, and trace components of turpentines depends on source and treatment during refining. For example, some of the factors which influence the composition of American and foreign gum turpentines include the species of pine, the age of the tree, and the season of turpentining; composition differences among steam-distilled turpentines depend on the age of the dead wood, the geographical location and type of fragment collected for processing, and the techniques used in refining.

The major constituents of turpentines of all origins are one, two, or three bicyclic unsaturated terpenes of the types: α-pinene, β-pinene, and 3-carene. (See Vol. **13,** p. 727.) The presence or absence of these terpenes can generally serve to identify the particular source of a turpentine. α-Pinene is common to all turpentines and is the major constituent of most American commercial products (Table I).

β-Pinene is present in substantial quantities in gum and sulfate turpentines, which are a source of technical grades of this terpene. β-Pinene is absent, or present only in trace amounts, in steam-distilled wood turpentine. Generally, this fact can be used to distinguish this turpentine from gum and sulfate products. In lesser known commercial products such as Indian turpentine (from the chir pine, *Pinus longifolia* Roxb.) or in turpentines currently of scientific interest only, as turpentine from western U.S. Ponderosa pine (11), 3- or 4-carene is the predominant constituent and the main

terpene. One sample from Ponderosa pine stumpwood contained 70% 3-carene (11). 3-Carene has also been found in substantial amounts in Swedish sulfate turpentine (30% in one sample) along with α- and β-pinenes.

TABLE I. Composition of American Turpentines.

Constituent	Gum	Steam-distilled wood	Sulfate wood	Destructively distilled wood
α-Pinene, %	60–65	75–80	60–70	[a]
β-Pinene, %	25–35	0–2	20–25	—
Camphene, %	—	4–8	—	—
Dipentene, other monocyclic terpenes, and *p*-cymene, %	5–8	15–20	6–12	—

[a] Reliable analyses of D. D. turpentine are not available; however, α-pinene is believed to be the chief terpene present.

The minor constituents of turpentines are primarily unsaturated monocyclic terpene hydrocarbons and include terpinolene, terpinenes, limonene and its *dl*-isomer, dipentene, and the corresponding saturated hydrocarbon, *p*-menthane (see Vol. **13,** p. 721). Dipentene occurs most frequently and relatively in largest amounts. *p*-Cymene, an aromatic compound frequently associated with terpenes and classed with them, and several menthadienes are also found in minor amounts in most types of turpentine. In steam-distilled turpentine, camphene, a very reactive bicyclic terpene, is found in minor amounts.

Trace constituents of turpentines are numerous. These include secondary and tertiary terpene alcohols such as fenchyl alcohol, borneol, and α-terpineol (see Vol. **13,** p. 731); terpene ketones and cineoles; and phenolic ethers (*q.v.*) such as estragole (methyl chavicole). Crudely refined turpentines contain also traces of resin acids, polymeric terpenes, and a variety of products usually found in plants and natural resins.

TABLE II. Typical Physical Properties of Commercial Turpentines.

Determination	Gum turpentine	Steam-distilled wood turpentine		Sulfate wood turpentine		Destructively distilled turpentine
		A	B	A	B	
$d_{15.5}^{15.5}$	0.868	0.8615	0.8625	0.867	0.867	0.854
n_D^{20}	1.470	1.4660	1.4661	1.470	1.468	1.470
Unpolymerized residue, %	2 (max.)	0.8	0.6	1.4	0.4	2
Aniline point, °C.	17.0	—	20.6	14	—	−4
Flash point, °F.	100[a]	101[b]	106[a]	100[b]	—	115[b]
ASTM distillation:						
Initial b.p., °C.	156	—	156	157	156	152
5%	—	156°C.[c]	—	159	158	156
10	161	—	157.0	159	—	158
30	—	—	157.4	—	—	—
50	163	157[c]	157.8	161	160	166
70	—	—	158.3	—	—	—
85	165	—	—	163	—	172
90	167	162[c]	160.0	164	166	174
95	171	—	162.1	170	170	176
97	—	—	170.0	—	180	—

[a] Cleveland open cup. [b] Open cup (type unknown). [c] Engler distillation.

In freshly distilled turpentines, other oxygen-containing compounds such as aldehydes may occur, but only in trace amounts. However, aged samples which have been exposed to the air may, as a result of oxidation, contain greater than trace amounts of oxygen-containing products of secondary origin; these include hydroperoxides, alcohols, ketones, and acidic materials.

Constants. The major constituents, bicyclic terpenes, determine the physical properties of a turpentine and its suitability for application, especially as a chemical intermediate. In spite of the great variance in chemical composition, however, the physical properties of commercial turpentines are surprisingly uniform (Table II).

Accordingly, most types are satisfactory with respect to the major use as a solvent and thinner for a variety of protective coating materials, waxes, and polishes.

Comparative values for the thermal and combustion properties of the various types of turpentines are not available. The following values, however, are believed to be typical for turpentines (regardless of type) which meet ASTM or Federal specifications: Burning characteristics, smoky flame; flash point (Tag closed cup), 91°F.; latent heat of vaporization, 68.6 cal./g. at 156°C.; specific heat (0–95°C.), 0.453; heat of combustion 1,460 kg.-cal./mole; and vapor pressure:

Temperature, °C.	−1.0	51.4	90.1	132.3	155.0
Pressure, mm. Hg	1.0	20.0	100.0	400.0	760.0

Reactions. The chemical reactivity of turpentines varies with the composition but generally is that characteristic of α-pinene, not only the most frequently occurring and dominant terpene constituent, but also one of the most active chemically. Accordingly, reactions that turpentine of high α-pinene content could undergo would include substitution by halogens; addition of halogen acids, hypochlorous acid, and nitrosyl chloride; reaction with phosphorus pentasulfide and hydrogen sulfide to form complex sulfur compounds and mercaptans; and addition of organic acids and alcohols to form esters and ethers, respectively. In the presence of Friedel-Crafts-type catalysts turpentine can be polymerized to hard resins. With acidic clay catalysts it can be isomerized to camphene. On pyrolysis it yields a mixture of acyclic and monocyclic terpenes along with a mixture of pyronenes. Oxidation yields hydroperoxides and/or ketones and alcohols depending on conditions of control. Also, turpentine can be hydrogenated to form chiefly pinane and can be hydrated to form a mixture of tertiary terpene alcohols, including terpin hydrate.

For the chemical activity and other properties of β-pinene and the less familar and minor terpenes comprising turpentines see *Terpene resins*; *Terpenes* (*mono-, cyclic*). For a discussion of the toxicity and flammability hazards of turpentine, see refs. (17,20).

Sources

The common source of all turpentines is the genus of coniferous trees known as *Pinus*. Turpentine is associated with both the oleoresin from the sapwood of living pines (gum turpentine) and with the resinous component of the boles or trunks and heartwood stumps of dead pines (wood, sulfate, and D. D. turpentine). Figure 1 summarizes in a general way these sources.

The biological origin of oleoresin, as described by Gerry (10), is within thin-walled parenchyma cells which in living trees are found in the outermost layers of sapwood next to the bark. These resin-producing cells occur in both vertical and horizontal arrangement. Through crossing and interconnection the cells become unified, and this gives rise to ducts or canals and permits passage of

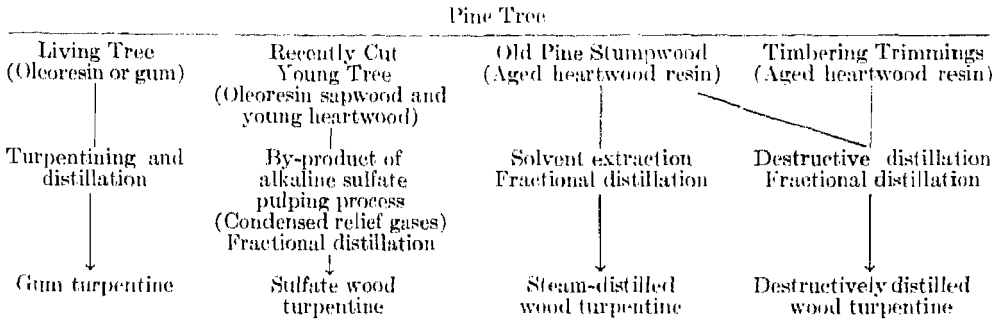

Pine Tree
Living Tree (Oleoresin or gum)
Recently Cut Young Tree (Oleoresin sapwood and young heartwood)
Old Pine Stumpwood (Aged heartwood resin)
Timbering Trimmings (Aged heartwood resin)
Turpentining and distillation
By-product of alkaline sulfate pulping process (Condensed relief gases) Fractional distillation
Solvent extraction Fractional distillation
Destructive distillation Fractional distillation
Gum turpentine
Sulfate wood turpentine
Steam-distilled wood turpentine
Destructively distilled wood turpentine

Fig. 1. Sources of turpentine (site of origin shown in parentheses).

resin. Upon natural or artificial damage (scarification as in turpentining) to the sapwood of a pine, some of the parenchyma cell walls are broken and the oleoresin exudes from these. The cells produce oleoresin during the growing or warm months of the year (March to November in southeastern United States) and remain alive and productive for several years if proper methods of scarification and other stimulation practices are used (see p. 386). Oleoresin is not the sap of the pine. The sap is an aqueous solution which is conducted through the sapwood by vertically extending tracheid cells derived from the cambium tissue of the pine.

Each year a portion of the older parenchyma cells in the inner layers of sapwood becomes impregnated with resin and ceases to function. This is the process of the transformation of sapwood to heartwood. The heartwood, which serves as a support for the tree, increases in size as a tree ages and becomes much higher in resin content than does the sapwood.

Steam-distilled wood turpentine is obtained from the resinous heartwood of the old pine stumps left over from lumbering operations (see p. 388). (It is estimated that heartwood of pine stumps contains as much as 25% resin, the heartwood of the bole about 7 to 10% resinous constituents, and the sapwood about 1 to 3% of oleoresin.)

Both the oleoresin-producing cells and, to a lesser extent, the resinous heartwood of young pine boles may be considered the site of origin of sulfate turpentine, obtained as a by-product during the manufacture of paper pulp by the sulfate pulping process (see p. 391). D. D. turpentine (see p. 390) also may be considered as arising from the resin constituents of both sapwood and heartwood of bole and lightwood (fragmentary wood left over after lumbering operations). Table III shows typical compositions of gum (oleoresin) obtained from the living pine in comparison with the resinous material extracted with solvent from the heartwood of dead pine stumpwood.

TABLE III. Approximate Compositions of Turpentine Source Materials.

Oleoresin (gum or dip) from living pine, %		
Turpentine	18	
Resin acids	65	Gum rosin
Neutral materials	7	Gum rosin
Water and trash	10	
Resinous extract from aged pine stumpwood, %		
Turpentine	14	
Pine oil	7	Wood rosin
Resin acids	71	Wood rosin
Neutral materials	8	

The species of pine which are capable of producing oleoresin and eventually heartwood stumps, or whose wood is suitable for pulping or distillation, are too numerous to mention. The composition of gum turpentine from 41 species of pines in the U.S. and Canada alone has been reported (18). However, at the present

time in the U.S., both gum and wood turpentine are produced commercially primarily from the oleoresin and stump heartwood of two species of pine, slash (*Pinus caribaea* Morelot) and long leaf (*Pinus palustris* Miller). Other species of pine are turpentined outside the U.S. (11,27). These include Scotch pine (*Pinus silvestris* L.), used in Europe and also used in Scandinavian countries for paper pulp manufacture during which sulfate turpentine is obtained as a by-product.

Production Methods

GUM TURPENTINE

Gum turpentine is one of the major products of the gum naval stores industry. It is the total volatile constituent of pine oleoresin, the nonvolatile portion of which yields gum rosin. The source of the raw material (referred to in the industry as gum or dip) for production of gum naval stores is various species of the living pine tree. See also *Rosin and rosin derivatives.*

In general, the basic methods of stimulating oleoresin production, its collection or harvesting, and its separation and refining into gum turpentine and rosin are similarly employed by all gum turpentine-producing countries. The U.S. and highly industrialized countries have, through scientific approach, modified and improved to a high degree the various production steps, especially the technique of stimulating gum or oleoresin flow. In some of the countries producing only minor amounts of turpentine these steps are crudely carried out, and this is reflected in the quantity, quality, and price of turpentine produced.

At present the area in the U.S. yielding gum naval stores raw material and the location of processing plants or stills are centered around Georgia (3,29) and include the adjacent states of Florida, Alabama, South Carolina, and the nearby states of Mississippi and Louisiana. This general area was formerly forested with several species of virgin pines which earlier were worked for naval stores. It has since been timbered and today is covered with second-growth pines primarily of the slash and longleaf varieties. It is estimated (24) that about thirty million acres of these two species of pines now exists in the South Atlantic and Gulf Coastal states, and of this amount about seven to eight million acres is of sufficient age to produce oleoresin.

Slash pine is preferred for oleoresin production since it becomes of a sufficient size for working when it is 15 to 25 years of age, whereas a longleaf pine must reach an age of 25 to 45 years before it is profitable to work for naval stores.

Turpentining. Artificial wounding (tapping, cupping, or chipping) and other methods of stimulating the tree to produce oleoresin and the systematic collection of the oleoresin are referred to in the industry as turpentining (8).

Chipping, carried out manually with a special hand tool called a bark hack, is a progressive upward streaking of the producing face of a tree. The shallow V-shaped incisions are referred to technically as *scarification.* Chipping must be done at intervals during the producing season (March to November), and its frequency varies, depending on weather conditions and stimulation practices. The oleoresin as it exudes from the tree flows down the chipped face from the uppermost streak and is guided into collection containers by various guttering arrangements (8). Generally the containers (1- to 2-quart capacity) are cup- or pan-shaped and are made of rust-resistant metals or of nonmetals such as clay. Several systems of cup and gutter arrangements are in use today. These include the Ball system, the one-piece apron

system, the two-piece apron system, the Herty system, and the latest devised (28), the spiral gutter arrangement.

The period of most rapid oleoresin flow is in the warmer months and directly after a streak has been made. The flow gradually tapers off between chipping periods. Trees are generally chipped at one-week intervals but, if the weather is particularly dry, this may be done as often as twice a week. Cups are emptied, generally at monthly intervals, into wooden or metal barrels located throughout the turpentined area. When full, the barrels are transported to the processing plant. Periodically gutters and cups must also be moved upward to prevent undue formation of "scrape," oleoresin from which most of the volatile constituents have evaporated. Scrape is removed at infrequent intervals from the tree and it is generally processed along with the usual run oleoresin.

The methods of chipping, location of the chipping (the face) on the tree, and optimum age for turpentining have been subjects of study for a great number of years by government agricultural agencies. The results of these investigations (30) have paid off in greatly increased yields of oleoresin and permit longer working life of trees. In recent years chemical treatment of the producing face has been found to increase gum flow and to permit longer periods of time to elapse between chippings. This has significantly reduced labor requirements. Several types of applicators for chemical stimulants have been devised; one that is in wide use is the squeeze bottle type (34). Chemicals currently recommended for use include 50% aqueous sulfuric acid for general use on most pines, and 2,4-dichlorophenoxyacetic acid (2,4-D) as a 2% aqueous solution specifically recommended for slash pines (7,30) (see Vol. **10**, p. 725; *Weed killers*). Infection of the face with a pine canker fungus was demonstrated (33) to cause above-normal oleoresin flow: however, the method has never been put into commercial practice.

In general, turpentining as practiced in the U.S. today is carried out by individual farmers or "producers" who sell their gum to distillers, and by "operators" who distill as well as harvest their oleoresin. It has been estimated (24) that there are about 13,000 turpentining sites in the southern states, about 10% of which are large acreages and are controlled by the larger operators. These few large turpentining areas represent about 80% of the trees worked.

Oleoresin Distillation. Oleoresin is separated into gum turpentine and gum rosin by distillation. In the U.S. batch stills are used for this purpose, although a continuous distillation still has been developed by the Olustee, Florida, Naval Stores Experiment Station (8,24). This is not yet in commercial use.

The simplest of the stills producing gum turpentine in the United States is the small direct-fired batch still known as a *fire still*. Formerly many of this type were in operation, but today turpentine from these stills represents a small fraction of the total amount of gum turpentine produced. The fire still is a large metal (usually copper) vessel of about 10- to 30-barrel capacity and with a removable head for charging the oleoresin. The head is fitted with an arm which directs the distillate into the condenser, which is a coiled copper pipe cooled in a water bath. The stills are generally mounted on brickwork and are heated externally on the bottom and lower sides by wood or oil.

The fire-still distillation generally requires about 2 hr. per batch. Oleoresin is charged into the vessel as it is delivered to the plant, along with 2 to 3 gal. of water per drum of gum. Intermittently during, or once towards the end of, the distillation ad-

ditional water is added to prevent overheating or burning. The distillate, a mixture of turpentine and water, after condensation is run into barrels or separators where the turpentine is drawn off from the top. Most operators run the turpentine through salt beds to remove remaining traces of water before barrelling or sending to storage tanks. (The residue in the still, gum rosin, is run through several beds of filtering media to remove trash, dirt, and sand before barrelling.)

The more modern distillation operations, which start with cleaning steps developed by the Olustee, Florida, Naval Stores Experiment Station (24), are carried out at central processing plants. The oleoresin is cleaned by diluting the crude oleoresin with about 35% of its weight of distilled gum turpentine. This dilution permits separation of trash, water, dirt, etc., by settling and/or by use of filter presses. Water-soluble impurities are removed by washing the turpentine solution of oleoresin with hot water. After gravity separation, the filtered, washed gum is then ready for distillation. In comparison with fire stills, the stills of central processing plants are larger, the charge is heated with internal steam oils, live steam is injected to effect steam distillation, the condenser systems are much more efficient, and the process in general is much more closely controlled.

Gum turpentine produced in ever-growing amounts by central processing plants meets ASTM and Federal specifications and generally is superior in uniformity and quality to gum turpentine produced in outmoded fire stills.

STEAM-DISTILLED WOOD TURPENTINE

Steam-distilled turpentine is the terpene product of greatest commercial importance produced by the wood naval stores industry. In the U.S. this industry, like others producing turpentine as a major item or as a by-product, is located near the areas yielding its raw material, the cut-over wastelands of the South Atlantic and Gulf Coast states. Other than Russia, which is believed to have a wood naval stores industry of undetermined size, the United States is the sole producer of steam-distilled wood turpentine.

The raw material of the wood naval stores industry is pine stumpwood and butt logs, remnants of some ten- to twenty-year or longer earlier lumbering operations involving virgin and second-growth stands of longleaf and slash pines. Stumpwood (especially that which has lost its bark and sapwood) of these species is high in resin. Rotting and subsequent sloughing off of the outer layers of the stump occur about ten years after the tree has been timbered. As a result only the rot-resistant resin-rich core or heartwood of the stump and portions of the taproot remain. Steam-distilled turpentine is obtained from the resinous content of this aged wood.

The butt log and stump of a virgin longleaf pine contain, respectively, on the average about 15 and 25% resin, whereas, the stumpwood of a second-growth pine contains about 15% resin. Steam-distilled turpentine, monocyclic terpenes, pine oil, wood rosin, and a gasoline-insoluble resin comprise the constituents of the resinous fraction of pine stumpwood. An analysis of a sample of aged virgin pine heartwood typical of that gathered for processing has been reported to contain 4% turpentine, 19% rosin, 4% of a gasoline-insoluble resin, 23% water, and 50% of cellulosic and lignin-type materials (14).

In the modern practice of stump removal, the stumps are pushed from the ground with a specialized "pushdozer," trimmed, reduced in size by blasting with dynamite,

sent to rail loading points, and then sent by rail to the stockpiles of the naval stores plants. For procurement of stumpwood, the larger wood naval stores producers maintain semipermanent woods camps central to areas which will provide raw material for several years. Collection is on a year-round basis except when inclement weather prevents operation of heavy equipment on rain-soaked terrain.

Extraction. The plant process for the recovery and refining of turpentine, other terpenes, and resinous products from pine stumpwood is referred to as the *steam and solvent method* (16,25). Basically, it consists of extracting the resinous content of the wood with solvents and then separating and refining the constituents of the extract, among which is steam-distilled turpentine. A detailed discussion with flow sheets of the process as employed by a major wood naval stores producer has been reported (15). The following operations are typical of most of the wood naval stores plants. At the processing plant the stumpwood, on arrival from the woods or plant stockpile, is first washed with high-pressure water to remove dirt and sand and then reduced to a size suitable for extraction. By some producers reduction of the wood to the desired size is accomplished stepwise: first it is fed to a rotary chipper, referred to in the industry as a "hog," and then through a hammer mill-type shredder. The resulting splinters or chips are moved by belt conveyer and charged through the top of a series of extractors, which are insulated vertical vessels. Some extractors have a capacity of approximately 15 tons of chips.

Hydrocarbon solvents, both aromatic and aliphatic, are used. Extraction of the resinous material from the chips is generally a continuous process. The solvent under pressure and increased temperature, 65–85 p.s.i.g. and 265–285°F. when an aliphatic petroleum fraction is used (15), is circulated progressively through extractors arranged in series before it is withdrawn from the system. For example, fresh solvent enters the first or No. 1 extractor at the bottom until the resin content of the chips is, for all practical purposes, exhausted. Withdrawal of the extract for refining into liquid and resinous products is from the last extractor in the series, which generally contains about ten extractors. At this point, No. 1 extractor is cut out of the series and fresh solvent is shunted to No. 2 extractor, which had been receiving solvent coming from the top of No. 1 extractor. When No. 2 extractor is exhausted of resin, the process continues by cutting out No. 2 and shunting fresh solvent to No. 3, and so on until the final extractor in the series has received fresh solvent. During this time the original No. 1 extractor has been steamed to remove excess solvent from the spent chips, the chips have been discharged to be burned as fuel, and the extractor has been recharged with fresh chips. At this point, extractor No. 1 is again cut into the system at the end of the series for extraction of its contents and the cycle is repeated as described above.

The liquid withdrawn from the last extractor in the series is rich in resin and is a solution of terpenes and crude rosin in the extraction solvent. Most of the solvent is removed in atmospheric evaporators connected in parallel and is recycled to the extractors as fresh solvent feed. The crude extract is passed through flash evaporators to remove remaining traces of solvent and then sent to fractionators. There, by means of steam and reduced pressure, the crude oils containing turpentine and other liquid wood naval stores products are separated from the crude wood rosin.

The crude oils are agitated with caustic soda to remove aldehydes and other materials which otherwise might impart undesirable odor and color to subsequent refined materials. Following the caustic treatment, the oils are sent to batch stills

through which they are fractionated into steam-distilled turpentine and other terpene-based products.

The type of solvent (aromatic or aliphatic) affects the total composition of the extracts, but is believed to have little effect on quality and quantity of turpentine extracted from the resinous heartwood chips; the difference in the extracts lies in the nature of the resinous products produced (32).

In addition to the major constituent, α-pinene, other products of importance accompanying the production of steam-distilled turpentine include wood rosin, dipentene, and pine oil (see Vol. 9, p. 587). Terpenes and associated products of commercial importance recovered in lesser quantities by the steam and solvent extraction of pine stumpwood include terpinenes, terpinolene, terpin hydrate, α-terpineol, and estragole.

Extraction of one ton of chips yields on the average approximately 85 lb. of crude oils, of which about 57% or 48 lb. is turpentine, according to Hightower (15). On an original wood basis, this amounts to about 2.4%, which is of the magnitude of that recovered by the destructive distillation of similar source material. For a similar wood naval stores operation, Humphrey (16) reports a volatile oil yield of about 12 gal. or about 90 lb. of crude oil per ton of wood chips processed. Generally, all turpentine offered by wood naval stores producers is refined to meet ASTM and Federal specifications for steam-distilled turpentine.

DESTRUCTIVELY DISTILLED TURPENTINE (D. D. TURPENTINE)

D. D. turpentine is one of a number of products obtained by a process involving destructive distillation of resinous softwoods. In the U.S. what remains of this industry is carried on primarily in the Southeastern section of the country, the locale of its source of raw material, the softwood pines.

The wood gathered for distillation, similar to that utilized in the steam and solvent extraction process, is dead down timber and stumps and trimmings left over from previous lumbering operations. The sapwood has generally sloughed off so there remains only the highly resin-impregnated heartwood, referred to by the industry as lightwood and fatwood. Waste wood of longleaf pine is preferred and used predominantly; however, Cuban pine, loblolly, and shortleaf pines are also suitable and are often represented in the wood collected (13). For distillation the wood is reduced to a suitable size, generally 4 ft. long with a maximum diameter of about 6 in. The various types of plant equipment used to distill and recover the products, including turpentine, of softwood distillation have been decribed (9, pp. 253–58; 13; 22). Horizontal cylindrical steel retorts are generally used, although vertical retorts and larger concrete retorts heated on the inside by cast iron flues have been employed. The retorts are usually mounted in series and may be opened at one or both ends, depending on method of charging and the size. Retort capacities are from ¾ to 10 or more cords of wood, depending on the distillation technique and type of products desired. The smaller retorts are air-tight and fired by wood, coal, oil, or gas. Most installations utilize as auxiliary fuel the noncondensable by-product gases formed during the distillation. Distillation requires from 16 to 48 hr., depending on the method of heating, products desired, and retort size, and averages about 30 hr. for the larger retorts. The products of distillation are conducted from the retorts into water-cooled condensers and are collected separately into several crude fractions. In addition to D. D. turpentine, separation of the condensed volatiles yields dipentene and other terpene

solvents, pine oil, various grades of pine tars and pine tar oils, and pyroligneous liquor. The still residue is charcoal. See *Wood*.

In a typical distillation (22), the condensate is collected in receivers called "tubs." During approximately the first half of the run, the condensate, consisting of the lighter oils which contain the turpentine and pyroligneous liquor, is pumped from the bottom. These lighter oils are then recombined with heavier oils obtained during the second half of the distillation, and the mixture is distilled in pot-type stills by means of steam coils and live steam. The fraction of light crude oils, which contains the turpentine, is treated with sulfuric acid and after the acid is removed, the light crude oils are again distilled, this time over caustic soda and through a fractionating column. From this distillation a crude turpentine fraction is obtained which on further rectification yields refined turpentine and crude dipentene.

The yield of turpentine from D. D. wood varies greatly and depends primarily on resinous content of the wood used and the efficiency of separation of the crude light oils. Smith (9, pp. 253–58) estimated that from a cord (about 4,000 lb.) of pine lightwood yields ranging from 35 to 140 lb. of refined D. D. turpentine may be obtained. This represents about 0.9 to 3.5% of the original wood.

Refined D. D. turpentine, which differs slightly in composition from other types, is manufactured to meet ASTM and Federal specifications.

SULFATE TURPENTINE

Sulfate turpentine is a by-product of the sulfate pulping process, a method especially suitable for manufacture of paper pulp from resinous woods. It is recovered from pulp mills in Sweden and Norway, and from softwood pulping mills in the South Atlantic and Gulf Coast sections of the U.S.

The mills in the U.S. recovering sulfate turpentine use exclusively southern pine as raw material; the species pulped includes longleaf, slash, loblolly, shortleaf, and Virginia pines. In contrast with the aged, highly resinous woods used in production of steam-distilled and D. D. turpentine, the wood used in alkaline pulping from which sulfate turpentine is recovered is relatively newly cut and much lower in resin content. The origin of turpentine from pulpwood is both the oleoresin of the sapwood and the relatively low-resin-content heartwood of the living young tree. The alkaline liquor used in the alkaline sulfate pulping process (see *Pulp*) brings about dissolution and dispersion of the noncellulosic constituents of wood, including the resinous material (or pitch as it is known in the paper industry), from which the turpentine is liberated by heat and steam.

In the sulfate pulping process, release of the turpentine occurs during the first third of the cooking cycle. During this stage, which lasts approximately 30 min., the steam pressure within the digesters builds up to approximately 60 to 70 lb. Under these conditions, relatively noncondensable gases such as ammonia, methyl sulfide, and methyl mercaptan are formed. They must be vented to retain true steam pressure. The oily organic portion of the condensate of these relief gases is crude sulfate turpentine. The presence of sulfur compounds gives an extremely disagreeable odor to the crude sulfate turpentine, which must therefore be refined before it is acceptable for any use. Refining methods are similar to those used for D. D. turpentine, that is, treatment with sulfuric acid followed by distillation over caustic soda. Generally, to aid removal of the odor, crude sulfate turpentine is treated with agents such as bleaching powder to oxidize the sulfides to less odorous materials.

Plants with modern efficient rectification stills are able to produce sulfate turpentine which meets all the requirements of ASTM and Federal specifications, including odor. It has been reported (24) that maximum yields of 19 lb. of crude sulfate turpentine per ton of air-dry pulp have been obtained from loblolly, shortleaf, and Virginia pine, and 30 lb. from longleaf and slash pine pulpwood. Generally a yield of over 15 lb. (0.75% of air-dry pulp) is exceptional for species other than slash and longleaf pines. Recovery of refined sulfate turpentine from the crude product is estimated to average about 80%.

Other naval stores products recovered as by-products from the sulfate pulping process include a small amount of poor-quality pine oil obtained from the condensed gases and tall oil (primarily a mixture of fatty and resin acids and the source of tall oil rosin recovered from the spent digesting liquors (see *Rosin*; *Tall oil*)).

Economic Aspects

The U.S. is the world's leading producer of turpentine and has held this position for years, as is shown in Figure 2 and Table IV.

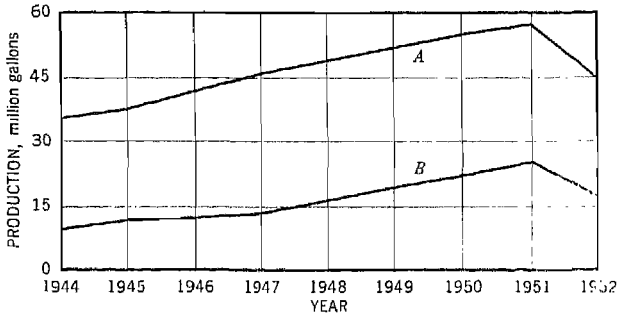


Fig. 2. World turpentine production (21). (*A*) World total; (*B*) outside U.S.

TABLE IV. U.S. Turpentine Production.

April 1–March 31	Gum		Steam-distilled wood		Sulfate wood		Destructively distilled wood		Total
	50-gal. barrels	% Total	50-gal. barrels	% Total	50-gal. barrels	% Total	50-gal. barrels	% Total	
1943–44	288,382	56.7	125,171	24.6	91,045	17.9	3,834	0.8	508,432
1945–46	244,252	50.0	129,101	26.5	110,262	22.6	4,516	0.9	488,131
1947–48	294,028	45.9	208,895	32.6	134,160	20.9	3,820	0.6	640,903
1950–51	271,880	38.4	237,080	33.4	194,180	27.4	5,410	0.8	708,550
1951–52	246,460	36.0	229,590	33.6	203,430	29.7	4,480	0.7	683,960
1952–53	217,360	38.5	174,820	31.0	169,560	30.0	2,930	0.5	564,670

Source: ref. (21).

Of the world's production of approximately 46 million gallons in 1952, the U.S. accounted for 28 million gallons or 60% (21). Greece, which has emerged since about 1945 as a major producer of turpentine (gum) from the Aleppo pine (*Pinus halepensis* Miller), accounted for approximately 15% of the production. France, a consistent major producer of turpentine (gum), principally from the maritime pine (*P. maritima* Lam), produced about 11% of the world's output in 1952. Other countries producing

gum turpentine in commercially significant quantities include Russia, Portugal, Spain, Mexico, Japan, and Germany.

In the five years preceding World War II, exports of turpentine from the U.S. ranged from 20 to 40% of the quantity produced. However, since World War II, exports have dropped considerably from a high of 29.4% for the crop year 1950–1951 to a low of 14.6% for the crop year 1952–1953.

Until recently, the production of gum turpentine in the U.S. has always exceeded that of the other types of turpentines by a considerable amount. Before 1945, gum turpentine production amounted to more than 50% of the combined production of all the other turpentines. Since that time, however, production of gum turpentine has steadily decreased, whereas that of steam-distilled and sulfate turpentine has generally shown yearly gains. For the 1952–1953 crop year, gum turpentine represented only 38.5% of the total production, whereas steam-distilled was 31%, and sulfate turpentine 30% (21).

The decline of gum naval stores production has been attributed largely to the lack of mechanization or the resulting dependence on abundant and cheap manual labor, especially for the working of turpentine groves. A shortage of labor occurred during World War II and since then the gum naval stores industry has been economically curtailed by the high cost of labor. More recently, an additional factor accounting for reduced gum turpentine production is the withdrawal of large acreages of pine land from turpentining by pulp manufacturers who have purchased them exclusively for pulpwood raw material.

The steady increase in production of both steam-distilled and sulfate turpentines is attributed, in general, to the more economical methods under which they are produced, improved methods of refining, and their acceptance as equal to gum turpentine in performance. Improvements in refining techniques particularly account for greater production and consumption of sulfate turpentine. Without efficient refining, sulfate turpentine was practically worthless because of its obnoxious odor. For a long time most of it was burnt as fuel or dumped into rivers or creeks.

The average monthly price for gum turpentine as posted by the Naval Stores Exchange at Savannah, Ga., for some recent years is shown in Table V.

TABLE V. Monthly Average Price of Gum Turpentine at Savannah, Ga.[a]

Year	Cents/gal.	Year	Cents/gal.
1939	19.44	1948	48.30
1940	25.18	1949	38.68
1941	49.52	1950	53.24
1944	77.67	1953	51.83

[a] After December 1951 prices are f.o.b. plant.

There have been brief periods when steam-distilled turpentine has been sold at higher prices than gum turpentine. Generally, however, steam-distilled turpentine is quoted at the same or at a somewhat lower price than is gum turpentine. This has been due mainly to support of gum turpentine prices by the government loan program on this commodity (31). Sulfate turpentine, until recently, has been priced substantially below gum or steam-distilled turpentines because of its inferior odor, but with the introduction of improved refining procedures it has commanded a more competitive price. D. D. turpentine has never been produced in sizable quantity and, like gum

turpentine, its production shows signs of declining. Today, several of the products of softwood distillation are being produced synthetically or by more economical methods. Accordingly, although several plants are still producing D. D. turpentine, this process has ceased to be as attractive as formerly. In terms of turpentine production, as shown in Table IV, destructive distillation of wood has been and continues to be of small importance.

Specifications and Standards

Solvent and Thinner Turpentine. Standards, specifications, approved test methods, and definitions of commercially acceptable types of turpentine have been established by "standards" institutions or societies and/or government agencies in several countries, including Canada, England, and the U.S. In general, physical and chemical specifications are designed to insure the consumer's receiving an unadulterated turpentine especially suitable for use as a solvent and thinning agent for oleoresin-based protective coatings.

U.S. standard designated turpentines are recognized as standard types by the American Society for Testing Materials and conform to physical and chemical specifications for turpentine established by the latter organization (ASTM Designation: D13-51) (1, p. 222), which are:

Appearance. Spirits of turpentine shall be clear and free from suspended matter and water.

Color. The color shall be "standard" or better.

Standard color. That color in turpentine which, when the liquid is viewed lengthwise through a colorimeter tube, requires a column of the turpentine 150 mm. in height to give a color equal to that of the No. 1 yellow Lovibond glass (12).

Odor. The odor shall be mild and characteristic of the kind of spirits of turpentine specified. If desired, deliveries shall conform to the odor of the sample agreed upon by the purchaser and seller.

Methods of testing. Properties comprising both U.S. and ASTM specifications must be determined in accordance with approved ASTM methods of sampling and testing turpentine (ASTM Designation: 233-51) (1, p. 257). See also Table VI.

TABLE VI. ASTM Specifications for Turpentine.

Property	Gum spirits of turpentine		Wood turpentine					
			Steam-distilled		Sulfate		Destructively distilled	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
$d_{15.5}^{15.5}$	0.875	0.860	0.875	0.860	0.875	0.860	0.865	0.850
n_D^{20}	1.478	1.465	1.478	1.465	1.478	1.465	1.483	1.463
Residue after polymerization with 38 *N* H_2SO_4, vol. %	2	—	2	—	2	—	2	—
Refractive index at 20°C.	—	1.500	—	1.500	—	1.500	—	1.480
Initial boiling point at 760 mm., °C.	160	150	160	150	160	150	157	150
Distilling below 770°C. at 760 mm., %	—	90	—	90	—	90	—	60
Distilling below 180°C. at 760 mm., %	—	—	—	—	—	—	—	90

Turpentine for use by all Federal agencies, including the Army and Navy, must comply with U.S. standards and specifically with Federal Specifications TT-T-801, TT-T-806, and TT-P-141. These specifications include, in addition to physical and chemical requirements, instructions for ordering, packaging, marking, shipping, inspecting, sampling, and testing.

Chemical Intermediate Turpentine. Specifications for turpentine used as a chemical intermediate are established generally by each individual manufacturer and vary, depending on the nature of the chemical derivative to be produced. Very little turpentine of Federal specification grade is used as such for chemical manufacture. In most cases, turpentine intended for chemical conversion has undergone additional refinement to remove or increase a particular constituent, commercial grades of α-pinene being an example (see p. 396).

Medicinal Turpentine. Standards, methods of testing, and description of turpentine approved for use in pharmaceuticals or medicinal preparations are contained in *The National Formulary (19)*. These standards recognize only a turpentine oil and rectified turpentine oil derived from the oleoresin of the living tree (as well as turpentine, the oleoresin itself, from *Pinus palustris* Miller and other *Pinus* spp. called also "gum thus" and "gum turpentine"). Accordingly, only gum turpentine within the prescribed physical specifications is approved for medicinal use. For internal use *The National Formulary* prescribes a rectified oil, prepared by steam distillation of gum turpentine in the presence of dilute sodium hydroxide solution.

There has not been a U.S.P. standard for medicinal turpentine subsequent to the twelfth revision (1942) (26). This deletion indicates the decreasing use of turpentine as such in modern medical practice.

Uses

The historical (colonial period to Civil War) uses for turpentine included a host of curative and medicinal applications of unfounded merit (9, pp. 29–30), its use as an illuminant and as a solvent for early types of paints and stains. Its use as an illuminant was short-lived and disappeared following the discovery of petroleum. Today, other than in the form of derivatives, turpentine finds little use in medicinal preparations (see, however, *Anthelmintics*, Vol. **1**, p. 939; *Emetics and expectorants*, Vol. **5**, p. 685; *Oils, essential*, Vol. **9**, p. 590).

Growing out of one of the original uses and now accounting for the largest consumption of turpentine is its use as a thinner for drying oil- and oleoresin-based paints, varnishes, and enamels. Formerly, the use of turpentine by the paint and varnish industry was about evenly divided between manufacturer and consumer. In the past thirty years, however, the use of turpentine by the paint manufacturer as the primary solvent for the resinous component of paint and varnishes has given way entirely to cheaper petroleum solvents.

Today, the still large demand for turpentine in this field is "over the counter sales" to professional painters and private individuals for use as a solvent and thinner to prepare and modify pigment pastes and ready-mixed paints for on-the-job application. Its consumption by amateur painters is to a large extent for use as a brush cleaner and storage medium. In paint and varnish formulations, turpentine functions in a multiple capacity. It is an excellent solvent for the oil, rosin, or synthetic resin film-former; it accelerates oxidation of drying oils; it reduces viscosity so that the coating may be smoothly and evenly applied; and its low surface tension permits it to

wet and penetrate wood surfaces, for which it has a natural affinity. Penetration of the turpentine carries the pigment-binding resin into the wood and thus results in firm anchorage of the protective coating. Its vapor pressure is of an order to permit adequate brushing time. The low percentage of turpentine which, on drying of the coating, does not evaporate, generally polymerizes and remains as a compatible component of the dried film-former.

The second largest but ever-growing demand for turpentine is for production of chemicals and chemical intermediates. A notable example, synthetic camphor, is one of the oldest pure chemical derivatives of the α-pinene constituent of turpentine (see *Camphor*). Originally, camphor and other chemical derivatives of turpentine were produced from turpentines of natural composition. Today, instead of using natural turpentines or U.S. standard grades of turpentine for chemical conversion, a high-purity concentrate of the desired constituent is used; for example, α-pinene, β-pinene, or dipentene, which are commercially available in tank-car quantities (see *Terpenes (mono-, cyclic)*). They are obtained by secondary fractionations of standard turpentines or by more efficient fractionation of turpentine source materials. High-purity grades of α- and β-pinene are produced to meet customer specifications which are dependent on the product to be manufactured.

More notable of the chemical intermediates from turpentine and their derivatives include α-pinene, β-pinene, dipentene, isoborneol, camphor, camphene, α-terpineol, terpin hydrate, chlorinated camphene, synthetic terpene alcohols, and reaction products of α-pinene and dipentene with phosphorus pentasulfide. These derivatives ultimately find their way into end products such as terpene resins (*q.v.*) and other synthetic resins, pharmaceuticals, insecticides, disinfectants, essential oils and other perfume constituents, and petroleum additives.

The smallest segment of the present-day consumption of turpentine, which depends on its excellent solvency for oils, natural and synthetic waxes, and resins, includes its use in cleaning compounds, printing inks, belt dressings, and floor, furniture, leather, and shoe waxes and polishes.

Bibliography

(1) ASTM, *Standards, 1952*, pt. IV.
(2) Brannan, C. F., *U.S. Dept. Agr., Service and Regulatory Announcements*, No. **170** (1952).
(3) Brown, C. N., *Forest Products*, Wiley, N.Y., 1950, pp. 181–86.
(4) Chadwick, T. C., and Matlack, M. B., *U.S. Dept. Agr., Tech. Bull.*, **596** (1937).
(5) Chadwick, T. C., and Palkin, S., *U.S. Dept. Agr., Tech. Bull.*, **749** (1949).
(6) Dupont, G., and Barraud, M., *Inst. Pin Bull.*, **60**, 155–56 (1929).
(7) Dyer, C. D., *Georgia Agr. Extension Service Bull.*, No. **564** (1950).
(8) Everhard, W. P., *U.S. Dept. Agr., Farmers' Bull.*, No. **1984** (1947).
(9) Gamble, T., *Naval Stores: History, Production, Distribution and Consumption*, Review Publishing & Printing Co., Savannah, Ga., 1921.
(10) Gerry, E., *U.S. Dept. Agr., Bull.*, **1064** (1922).
(11) Goldblatt, L. A., and Burgdahl, A. C., *Ind. Eng. Chem.*, **44**, 1634 (1952).
(12) Grotlisch, V. E., *Naval Stores Rev.*, **63**, 15, 20–21 (1954).
(13) Harper, W. B., in Furnas, ed., *Rogers' Manual of Industrial Chemistry*, 6th ed., Van Nostrand, N.Y., 1942, Vol. I, pp. 677–700.
(14) Harris, G. C., *Tech. Assoc., Pulp Paper Ind., Monograph Ser.*, No. **6**, 167 (1948).
(15) Hightower, J. V., *Chem. Eng.*, **54**, 119 (1947).
(16) Humphrey, I. W., *Ind. Eng. Chem.*, **35**, 1062 (1943).
(17) Lehmann, K. B., and Flury, F., *Toxicology and Hygiene of Industrial Solvents*, Williams and Wilkins, Baltimore, 1943.

(18) Mirov, N. T., *J. Forest Products Research Soc.*, 4, 1–7 (1954).
(19) *National Formulary*, 9th ed., 1950, p. 558.
(20) National Safety Council, *Industrial Data Sheet*, Turpentine D-Chem. 12, Chicago, 1951.
(21) Naval Stores Review, *Intern. Yearbook*, 1953.
(22) Nealey, J. B., *Chem. & Met. Eng.*, **43**, 20–21 (1936).
(23) Palkin, S., *U.S. Dept. Agr., Tech. Bull.*, **276** (1932).
(24) Panshin, A. J., Harrar, E. S., Baker, W. J., and Proctor, P. B., *Forest Products—Their Sources, Production, and Utilization*, McGraw-Hill, N.Y., 1950, pp. 417–53.
(25) Peterson, J. M., *J. Chem. Educ.*, **16**, 317 (1939).
(26) *Pharmacopœia of the United States of America*, 12th revision, 1942, p. 336.
(27) Pojoski, B., *Naval Stores Rev.*, **61**, 16–17, 24–25 (1952).
(28) Schopmeyer, C. S., *Southern Lumberman*, **187**, No. 2345, 112–15 (1953).
(29) Shirley, A. R., *Georgia Agr. Extension Service Bull.*, No. **532** (1947).
(30) Snow, A. G., Jr., *Southeastern Forest Expt. Sta.*, Paper No. **32** (1954).
(31) *U.S. Dept. Agr., Inform. Bull.*, No. **13**, Revised December 1953, p. 89.
(32) U.S. Pat. 2,193,026 (March 12, 1940), L. C. Hall (to Hercules Powder Co.).
(33) U.S. Pat. 2,436,359 (Feb. 17, 1948), G. H. Hepting (to U.S. as represented by Secretary of Agriculture).
(34) U.S. Pat. 2,431,745 (November 28, 1950), C. S. Schopmeyer (to U.S. as represented by Secretary of Agriculture).

W. D. STONECIPHER

TYNDALL EFFECT. See *Colloids*, Vol. 4, p. 228.

TYPE METALS AND PLATE MATERIALS

Type metals are alloys of lead, tin, and antimony in various proportions. They have been in use for over five centuries, and their use has continued to this day because of several advantages. The alloying ingredients are available in ample supply, the alloy compositions are not too critical, they have a low melting point and good castability, and they have a minimum contraction upon solidification. They provide clean, sharp casts of type characters and can be readily machined and soldered. Type metals can be corrected for composition, cleaned, drossed, and remelted with fairly simple equipment and at a low cost. The hardness of the alloys can be increased or decreased by varying the percentages of tin and antimony added to the lead.

This article also discusses nonmetallic plate materials (see p. 404) and certain other materials used in letterpress printing, such as molding materials. Processes other than the letterpress process are described under *Printing and reproducing processes*.

Type Metals

Table I gives the composition and other data for five metals, foundry type, Linotype, Monotype, stereotype, and electrotype. See also Figs. 1*a–c*. It will be seen that in composition they do not differ very widely, but it must be remembered that their manner of use is different.

Foundry type is used when type is set by hand, which is the oldest process of type setting. The original typesetting (type-casting) machine was the *Linotype*, and this was followed by the *Monotype*.

Type prepared by any of these typesetting processes may be printed from directly in the letterpress process of printing. Alternatively, the original type settings may be used as patterns from which duplicates, or replicas, are made by the *stereotype* process,

the *electrotype* process, or other processes; the duplicate plates are then used in the letterpress printing process.

When other printing processes are to be used, such as lithography or gravure

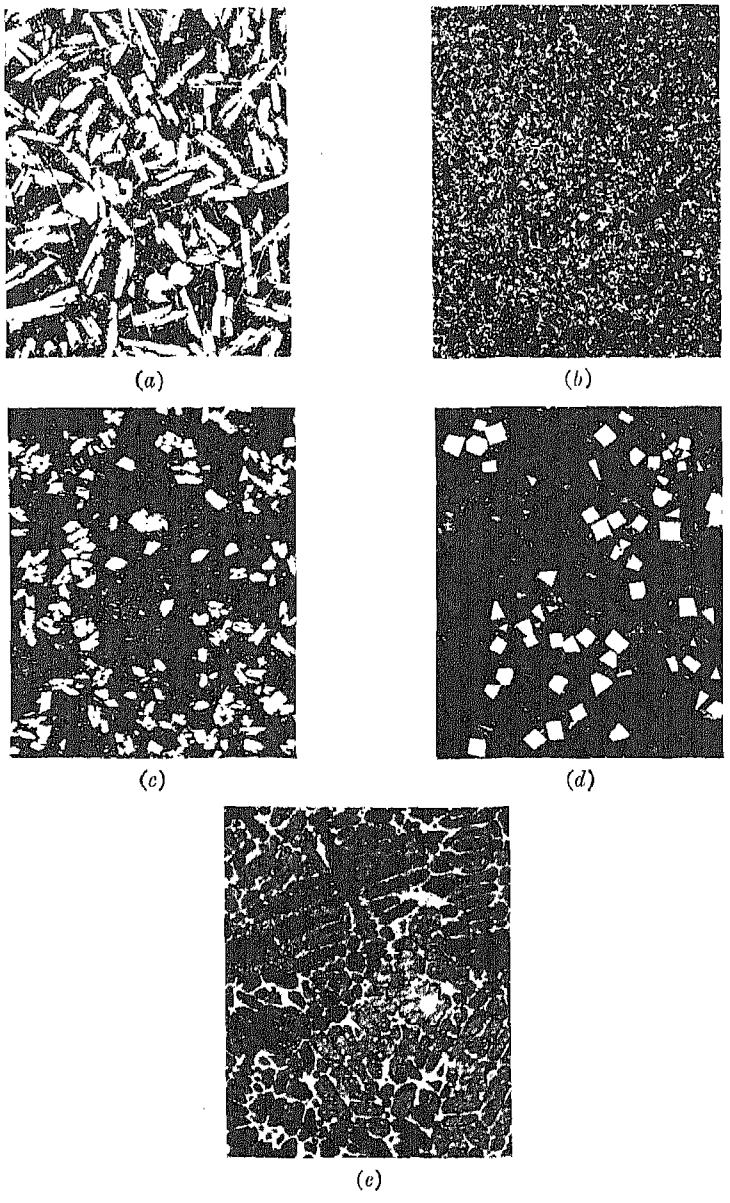


Fig. 1. Photomicrographs of representative type metals (× 100): (*a*) foundry type; (*b*) Linotype; (*c*) Monotype; (*d*) stereotype; (*e*) electrotype. (*a, b, e*, courtesy E. W. Blatchford Co., Division of National Lead Co.; *c* and *d*, courtesy Imperial Type Metal Co.)

printing (see *Printing and reproducing processes*), carefully made ink impressions on paper or on transparent film material are made from the type, and these "proofs for reproduction" are used as copy in making the plates or printing cylinders.

TABLE I. Typical Composition and Properties of Type Metals.

Kind	Composition, % Pb	Sn	Sb	Brinell hardness number[a]	Liquidus, °F.	Solidus, °F.	Reference
			Foundry Type				
Soft	70	10	20	30	553	462	1,2,6
Typical composition	62	13	25	34	617	462	1,2,6
Special	54	18	28	—	637	462	1,6
Hard (1.5% Cu)	60.5	13	25	—	—	—	1
Hard (1.5% Cu)	58.5	20	20	—	—	—	1
Hard (2.0% Cu)	61	12	25	—	—	—	5
			Linotype				
Standard	86	3	11	19	477	462	1,2
Hard	84	5	11	22	475	462	1,2
Eutectic alloy	84	4	12	22	463	462	1,3,2
			Monotype				
Ordinary	78	7	15	24	503	462	1,2,6
Display	75	8	17	27	520	462	1,2,6
Case type (Lanston *standard*)	72	9	19	28.5	546	462	1,2,6
Case type	64	12	24	33	626	462	1,2,6
Rules	75	10	15	26	518	462	1,2,6
			Stereotype				
Flat plate	80	6	14	23	493	462	4,2
General	80.5	6.5	13	22	485	462	5,2
Curved plates	77	8	15	25	505	462	1,2,6
			Electrotype				
General	95	2.5	2.5	—	578	475	1,2
General	94	3	3	12.4	568	475	3,2
Curved plates	93	4	3	12.5	561	473	2

[a] 250-kg. load, 30 sec. (ref. 4).

Photoengraving (see Vol. **11,** p. 127) also produces relief plates (image-surface raised) which may then be used by the letterpress process, or as original patterns for making duplicate plates.

Phototypesetting was commercially introduced about 1948 and is being used increasingly. In this device, each letter is photographed, and a plate of the copy is then made, usually by lithography. The printing industries refer to this new method of composition as "cold-type," as compared with the "hot-type" processes in which type metals are used.

Foundry Type Metal. Foundry type, set by hand, is widely used, wherever high quality is required. For example, much advertising display matter is set by hand with foundry type. The type is die-cast, on a special machine, against brass molds, or dies, that are prepared from a master design. This casting is done by type-founders, who supply the type to composing rooms. Foundry type is not recast in composing rooms, as are Linotype and Monotype metals.

After use, the type is broken up and each letter or character is distributed in the type cases for subsequent re-use. Thus the type may be printed from, or molded

(*i.e.*, used as a pattern in molding), many times. Maximum hardness is therefore desirable, to resist abrasion from wear, and mashing from molding pressures.

From 1.5 to 2.0% copper is added to foundry type metal to obtain the hardest and most wear-resistant alloy. The antimony content may be as much as 25% in the hardest foundry type metal and is generally maintained at above 20% even in the softest. The tin content may vary from 20% in the hardest alloys to 10% in the softer foundry type.

Linotype Metal. The Linotype machine uses brass type molds, which are female, the shape of the letter being depressed in the surface. The machine assembles a complete line of these, and then a cast, or slug, of the complete line is made in Linotype metal. The brass type molds are then distributed by the machine. The type metal, after it has been printed from or molded, is remelted and used in the next type-casting operation.

A type metal having a short temperature range during solidification and a lower melting point than foundry type metal was found satisfactory for the machine. Although other line-slug casting machines, such as the Intertype and the Ludlow, have been introduced since the Linotype and use the same metal, the name Linotype metal remains in use.

An antimony content of 11–12% and a tin content of 4–6% is used in the Linotype metal. It is to be noted that special care must be taken in avoiding contamination of Linotype metal with copper and zinc. The construction of the casting unit of line-slug machines is such that the flow of the metal may be impaired as a result of contamination by either of these impurities.

Strip material, such as rules and spacing material, is cast on the Elrod machine. Linotype metal is generally used for the purpose.

Linotype is widely used for newspapers, books, magazines, and the like. No proof change can be made without destroying and recasting an entire line, and therefore, where many changes are likely, or if much special type is to be used, Monotype is more convenient.

Monotype Metal. This alloy is designed for use in the casting machine developed by the Lanston Monotype Machine Co. The machine die-casts a single character at a time, hence the name Monotype. Brass molds are used, and the arrangement of the machine is such that type distribution is eliminated. A rapid cooling of the cast makes possible a high rate of production and the use of a relatively hard alloy, even though it is accompanied by a high melting point. After use, the type metal is melted for subsequent recasting. Thus this system of type casting provides a continuous supply of new, sharp, unused type. Every effort is made to obtain type with the Monotype machine that will compare favorably in service with foundry type. The antimony content of Monotype metal may vary from 15 to 25%, while the tin percentage may vary from 7 to 12%. The metal has excellent casting characteristics and must withstand printing pressures, molding pressures, and wear. The molding pressures for electrotyping, stereotyping, plastic-plate production, and molded-rubber plate production may amount to as much as 2500 p.s.i.

Stereotype Metal. Stereotypes are duplicate plates for letterpress printing. They are replicas of a type form and are made by pouring molten stereotype metal against stereotype mat, or matrix, which is a paper composition mold of a type form. The mat material consists of a uniformly thick sheet of paper, about thirty-thousandths of an inch thick, that has been lightly calendered during manufacture. The surface is

coated by applying a film of a "gum" solution. This solution is a proprietary formula for each manufacturer, and it usually contains some silicates and aluminates of alkali metals. The sheet material is conditioned to absorb water, up to about 20% by weight, after which it is placed face down on a type form. A resilient backing, of cork and felt sheets, is placed against the mat, and a pressure roller is passed over the assembly. The pressure of the roller causes the mat to be forced between and around the letters, forming an accurate paper composition mold of the type. The mold is then dried and placed in a suitable metal frame, wherein molten stereotype metal is poured against the mat surface. The pouring temperature of the metal should not exceed 625°F. The paper composition does not burn or char at this temperature, and, after solidification upon cooling of the metal, a cast, or stereotype, is thereby obtained. The stereotype is used as a printing plate. The stereotype process permits a number of duplicate plates to be made from a type form very quickly. Thus the stereotype process is convenient where the identical advertisement is to appear in a number of newspapers simultaneously; the mats are sent to the composing rooms of the different newspapers.

The thickness of the casts seldom exceeds ¼ in. In casting stereotypes for use on rotary newspaper presses, the mat is held in the curved position by vacuum in a curved casting box. A slight pressure is applied to the molten metal after it has been cast, and rapid cooling is effected. The curved stereotype, cast in this fashion, readily fits the press cylinders after a minimum of finishing operations. Since stereotypes are printing plates and are sometimes used as patterns for making other duplicate plates, the stereotype metal must have the maximum hardness possible for the pouring temperature used. The use of paper-composition mats limits the pouring temperature of the metal to about 675°F. for the average mat without scorching. Most stereotype casts are made at a metal temperature of about 625°F. Stereotype metal must also have good castability to reproduce the detail present in the mat. With care, good equipment, and carefully prepared material, it is possible to produce stereotypes having a printing quality comparable to electrotypes. Stereotypes are frequently plated with nickel, iron, or chromium to provide increased surface wear for printing long runs.

Stereotype metal usually contains from 13 to 15% antimony and from 6 to 9% tin. Stereotypes are remelted after use, and, therefore, the contamination of the metal with impurities of other printing metals requires a careful control of composition and purity.

Electrotype Metal. In the electrotype process there are two steps. First, a mold or impression is made, which is female, the printing areas being the bottom face of the depressions. On this a thin electrotype shell of copper is deposited by electrolysis. This shell is then backed up with electrotype metal, which is simply used as a fill-in material to give sufficient rigidity.

Starting with a type form, made by any of the type-setting processes, or a printing plate made by photoengraving, a mold of the form is made in a molding material by direct pressure between two platens. For the molding material, wax was once widely used but is now largely replaced by a thermoplastic resin, a vinyl acetate–vinyl chloride copolymer. Sheet lead may also be used as the molding material.

The mold is then connected as the cathode in electrolysis in a copper sulfate solution. Wax molds are covered with powdered graphite to make them electrically conducting. Plastic molds are coated with a film of chemically deposited silver. Copper is electrodeposited to form a shell, about 0.008–0.014 in. thick. Sometimes nickel is deposited first, to a thickness of 0.001–0.002 in., to give a harder printing surface, and is backed up by copper.

The back of the shell is then tinned by melting a film of electrodeposited tin, or a sheet of tin foil that has been previously applied and fluxed. While the tinned surface is fluid, molten electrotype metal is poured into the back of the shell at a temperature of about 650°F. Good adherence of the electrotype metal to the shell is thereby obtained. An overall thickness of metal of 0.125–0.275 in. may be poured, depending upon the kinds of plates being made.

Until about 1940, casting was performed entirely in flat cast iron pans. All curved plates were formed from plates made flat. Two types of machines are now available for casting curved plates. In each of them the shell is held in the curved position while the cast is made. Centrifugal casting of curved plates is an interesting and recent development in electrotype manufacture. The largest volume of backing up is still done in flat cast-iron pans. Some mechanized operations and the use of metal pumps speed up the operation and improve the quality of the work.

Since electrotypes have a printing face of electrodeposited copper or nickel, electrotype metal does not have to be as hard as other type metals. The average composition used for flat plates is 3% antimony, 3% tin, and the balance lead. When the finished electrotypes are to be used as molding patterns for other duplicate plates, the electrotype alloy is usually hardened by increasing the antimony content by 2 or 3% and the tin by 0.5%. For curved plates, the tin content is usually increased to 4–6% and the antimony content to 3.5–5%.

Electrotype metal can be formed by pressure. Thus the printing plane of an electrotype can be accurately formed by applying local or overall pressures on the electrotype metal back of the plate as needed. Curved electrotypes seat themselves to the curve of plate cylinders on rotary presses because of the ductility of the electrotype metal. By comparison, stereotype metal is too brittle to finish.

GENERAL CHARACTERISTICS OF TYPE METALS

Type metals melt and cast easily and are not especially sensitive to temperature, composition, corrosion, and oxidation. They do not readily segregate upon solidification. In the casting of type metals in metal molds for foundry type, and in the type-casting machines, rapid cooling is necessary to have a completely solid cast for ejection at the speed of the casting machine. This cooling causes solidification at the faces of the mold because it is chilled there first. There is a tendency for porosity in the centers of the type characters and the slugs because the air in the mold escapes with difficulty. The injection of the molten metal should be rapid enough to assure a good fill of the mold, and the temperature of the metal should be high enough to avoid premature solidification.

It has been stated that there is a slight expansion of type metal upon solidification and that this is the cause of the sharpness of definition of type characters. Actually, all type metals contract slightly upon solidification (3,8,9), and sharpness is caused by rapid chilling at the surface of the mold.

The composition of the type metals for machine casting is not critical. The U.S. Government Printing Office used an alloy of 82% lead, 12% antimony, and 6% tin for many years as a "universal" metal instead of separate Linotype, Monotype, and stereotype metals. This practice reduced the need of segregating and correcting the several kinds of metals. It is true that some improvement in quality of casts can be obtained by using a type-metal composition especially formulated for the purpose.

In the casting of type metals, the pouring temperature should be kept high enough

above the liquidus temperature to obtain solidification in the time required. In casting stereotype metal, the temperature of the metal as poured is about 100°F. above the liquidus, whereas Monotype metal should be cast at about 200°F. above the liquidus.

Type metals containing 12% or more of antimony will tend to segregate during slow cooling but will make homogeneous castings when chill cast. Segregation is likely to occur in molten metal in pots, and stirring should be used to maintain a uniform composition. Stirring of type metal in pots will increase the rate of formation of dross, and this causes a loss of metal. Stirring of the metal pots should be done carefully and in a manner to minimize surface oxidation of the molten metal. The tin and antimony oxidize first and are found to be present in the highest percentages in the dross. The tendency for type metals gradually to lose tin and antimony through drossing can be overcome by the regular use of correction metals. These metals contain high percentages of tin and antimony as compared with the original formula of the type metal. Regular analyses and the use of correction metals as a control procedure will permit the maintenance of a nearly constant composition of the type metals over a long period of use.

Type metals should be clean and free from dross and oxide as they are used. These substances form as a skin on the surface of the molten metal. Overheating of the metal, excessive stirring, and the use of compressed air or steam in metal cleaning will greatly accelerate the formation of dross. The metal should be skimmed. During use, the metal should be ladled or pumped from below the surface. In the operation of type-casting machines, dross seldom is introduced into the casts; but it may clog the injection nozzles and feed lines of the machine and cause mechanical difficulties.

The dross from type metal contains high percentages of unoxidized metal that has become mechanically entrapped in the oxide. Some of this metal can be recovered by treating the dross separately with a flux material, which may contain tallow, palm oil, rosin, ammonium chloride, and a reducing agent.

The size of the grain of type metal is determined by the rate of cooling during solidification. Smaller grain size may be obtained by increasing the rate of cooling, or by decreasing the temperature of the molten metal at the time of pouring or by both. A finer grain size is generally preferred, particularly in electrotyping and stereotyping. The addition of approximately 0.1% of arsenic, or 0.15% of tellurium, will produce a fine grain in electrotype metal and does not seem to affect the hardness or ductility adversely.

Effect of Impurities. Type metals can be readily contaminated by small amounts of other unwanted metals. The casting behavior and properties of type metals may be seriously and adversely affected by the presence of such impurities. New type metals are usually prepared by secondary metal refineries and generally are not as pure as the virgin constituent metals. With the exception of foundry type metal, all the type metals are repeatedly remelted and recast. Efforts are made to keep them segregated by class and to keep them free from other kinds of scrap metal that may be used in the printing operations. In spite of precautions, there is always the possibility of contamination of the type metals by dross and oxides and by other metals, especially copper and zinc. The impurities known to be deterimental to type metals are copper, zinc, aluminum, arsenic, and nickel (except when added for specific reasons as discussed later). Although type metals are usually processed in iron equipment, iron in

the type metal is considered detrimental, for the presence of small amounts may increase the drossing.

Small amounts of copper in type metal will combine with the tin to form long needle-like crystals that may clog the orifices of type-casting machines. The compound formed usually contains 99.6% tin and 0.4% copper, and it is known as hard tin. Crystals of this alloy will form if as much as 0.1% copper is allowed to contaminate the molten type metal. Copper-tin and tin-copper alloys form fairly readily in all percentages. In electrotype metal, these crystals present hard spots and promote segregation. Both of these conditions interfere with the satisfactory curving of flat electrotypes. Nickel has an effect similar to copper. As previously discussed, copper may be added to foundry type for additional hardness.

The presence of 0.1% or more of zinc will affect the castability of type metal and give a granular metal. The same effects are caused by the presence of small amounts of aluminum.

The presence of as much as 0.15% arsenic does not seem to have any injurious effect on type metal; indeed, the addition of as much as 0.75% arsenic to type metal has been made in some cases to improve castability and to increase hardness. Nevertheless, arsenic is considered a harmful impurity in type metal. Some users report a decrease in the fluidity of the metal because of the presence of arsenic. There are some reports of arsenic causing corrosion of the orifices on type-casting machines.

In general, all the impurities mentioned increase the formation of dross and the attendant loss of metal. The metal also requires more attention because of the correction treatment required to get rid of the impurities.

Age Hardening of Type Metals (5,10,12,15). Electrotypes are harder to finish and more difficult to curve if these operations are not performed the same day they are cast. It has been found empirically that measurements of the conventional hardness correlate well with the ability of the metal to resist deformation. Measurements of the hardness of electrotype metal as cast and after various time intervals indicate a definite increase in hardness over a period of 2 weeks. Most of the increase took place within the first 24 hours after casting. The total increase in hardness for the 2-week period was about 50%. A study of this characteristic revealed that electrotype-metal age hardening is more pronounced than in the other type metals. This effect is favored by the small percentages of tin and antimony in electrotype metal as compared with the other richer type-metal alloys.

In a solid solution, the solubility of antimony in lead decreases with a decrease in temperature below the eutectic point. Therefore, age hardening is possible by rapid cooling of the alloy. Age hardening of electrotype metal can be accelerated by heating the metal to elevated temperatures. By heating ½ hr. at 455°F. (235°C.), followed by quenching in cold water and reheating at 185°F. (85°C.), the electrotype metal attains maximum hardness in 1 hr. Somewhat greater hardness is attainable by pausing for an hour or two at room temperature before reheating. This property has been utilized to a limited extent in hardening electrotypes for special purposes, such as mat patterns and embossing plates.

Plate Materials

This section discusses nonmetallic materials that can be used for the printing plates in the letterpress process of printing. Some of these materials can also be used for making the molds from which duplicate plates are made.

Plastic Plates (11). Since about 1917, some commercial application of duplicate plastic plates has been made. The first plastic plates were of a thermosetting phenol-formaldehyde resin. The successful use of a thermoplastic Vinylite copolymer for the plate material was developed about 1930. A continuing increased use of duplicate plastic plates in letterpress printing has taken place. The plates are used for advertising plates, book plates, folding-box printing, and a variety of commercial types of printing.

In making plastic plates, a mold (female) is first made of the form. Thermosetting phenol-formaldehyde resins are used as the molding medium. The plastic plates are then formed in this mold.

Almost all plastic plates are made of a thermoplastic resin, a vinyl acetate–vinyl chloride copolymer. The resin is provided in granular and sheet form and is molded with heat and pressure in a thermosetting mold. Thickness bearers are used to regulate the distance between the press platens at full pressure. Thus the plate thickness can be controlled. After forming the plate, it is cooled, and it may be used as is or mounted on a suitable printing base. The plates may be ground or shaved on the back to obtain a uniform desired thickness.

Some plastic plates are made of a thermosetting phenol-formaldehyde resin, which is available in powder and granular form and are impregnated sheet materials. The same general procedure is followed in plate-making as is used for thermoplastic plates.

The PPR Molding Process (16) employs a sheet of a thermoplastic resin, a vinyl acetate–vinyl chloride copolymer, as the molding medium in the manufacture of electrotypes. The mold is formed by heat and pressure, a silver film is applied to the surface, and an electrotype shell is electrodeposited against the mold surface. Thermosetting phenol-formaldehyde resins are used as the molding medium in the manufacture of plastic and molded-rubber printing plates.

A variety of plastic-surfaced wood, plastic-surfaced laminates, and plastic sheet materials have been used for engraving original printing plates mechanically or by hand. This is performed essentially as woodcuts are made. Such plate materials find little application in the printing industry.

Rubber Plates (11,14). The first printing from original rubber plates utilized a rubber-faced plate material on which hand or mechanical engraving of the plate was done as in making a woodcut. One of the materials had a hard-rubber cored base and a film of about $\frac{1}{8}$ in. of a semihard rubber composition. Another material was a vulcanized rubber-canvas sheet. The surface compositions of these and similar materials were suitable for cutting and engraving. About 1926, the introduction of the Jean Berte process of cutting rubber plates and the use of water-color inks with these plates intensified interest in cut rubber plates in the U.S. All the rubber-plate compositions were formulated with natural rubber.

About 1932, duplicate molded-rubber plates became a commercial reality. Uncured rubber material is supplied in sheet form and is molded with heat and pressure in a mold made of thermosetting plastic. Vulcanization of the rubber takes place during the molding operation. Thickness of the plates is controlled by the use of thickness bearers. The plates may be ground on suitable machines to correct to uniform thickness if desired. By laminating either a wire screen, a perforated sheet metal, paper, or cloth in the rubber plate material before molding, the dimensional changes that occur during molding can be eliminated or reduced.

The original rubber compositions used natural rubber, but plates of this material were caused to swell and break up by the action of the oil inks. Synthetic rubbers of the Buna-N type were found superior for use with this kind of ink. The GR-S and butyl rubbers are also used for molded-rubber plates but are not as resistant to the action of oil inks as Buna-N. Natural rubbers are preferred for plates to be printed with flexographic inks.

Celluloid Plates. The Scan-A-Graver machine was developed by the Fairchild Camera and Instrument Co. and introduced to the newspaper industry about 1948. This method does not utilize a single machine, material, or skill of the photoengraving process, yet produces plastic halftone plates of good printing quality. The plate is formed by an indenting of the surface by means of a heated stylus that moves rapidly up and down. The plate is formed around a cylinder and rotated so that a continuous-dot pattern is achieved over the entire surface. The depth of the indentations is varied by an electric current that is governed by a photoelectric scanning device that scans the original photographic copy. The machine is rapid and ingenious.

The Scan-A-Graver uses a transparent sheet of cellulose nitrate about 0.020 in. thick. The printing surface is colored with a dye so that the engraved pattern can be observed as it is formed. These celluloid plates are finding ready acceptance and will yield press runs of 30,000 good impressions.

Norlan Plates. A German machine, the Klischograph, was introduced to the U.S. in the fall of 1953. This machine also mechanically engraves a halftone letterpress printing plate. A cutting stylus is used, and the width of cut is controlled by a photoelectric scanner that scans photographic copy only. The machine is sold in this country under the trade name Engrav-A-Plate. The plate material is probably an opaque white-pigmented polyvinyl chloride sheet, possibly containing a limited amount of acrylate, about 0.020 in. thick. It may be used directly for printing or for making wax-composition electrotype molds or stereotype mats.

Bibliography

(1) Dean, R. S., Zichrick, L., and Nix, F. C., *Trans. Am. Inst. Mining Met. Engrs.*, **73**, 505 (1926).
(2) "Electrotyping in the Government Printing Office," Printing Industry of America, Joint Research Bulletin PL-2, Government Printing Office, 1949.
(3) Endo, H., *Sci. Repts. Tôhoku Univ.*, Ser. **1**, **13**, 193 (1924).
(4) Fry's Metal Foundries, Ltd., *Printing Metals*, London, 1936.
(5) Gonser, B. W., *Intern. Assoc. Electrotypers and Stereotypers, Tech. Bull.* 4 (Sept. 1, 1937).
(6) Gonser, B. W., and Epstein, S., *Metals & Alloys*, 8, 3–7, 59–62, 63–70, 72, 117–21 (1937).
(7) Gonser, B. W., and Winkler, J. H., in *Metals Handbook*, American Society for Metals, N.Y., 1948, pp. 957–59.
(8) Hondo, K., and Kikuchi, R., *Sci. Repts. Tôhoku Univ.*, Ser. **1**, **21**, 579 (1932).
(9) Matsuyama, Y., *Sci. Repts. Tôhoku Univ.*, Ser. 1, **17**, 1 (1928).
(10) Morgan, R. A., Swenson, L. G., Nix, F. C., and Roberts, E. H., *Trans. Am. Inst. Mining Met. Engrs.*, **78**, 316 (1928).
(11) "Rubber and Plastics Used in the Printing Industry," Research and Engineering Council of the Graphic Arts Industry, Inc., PL-3, Washington, D.C., 1953.
(12) Schwarz, R. H., and Winkler, J. H., "Heat-Treated Electrotypes," Graphic Arts Tech. Conf., Graphic Arts Div., A.S.M.E., Philadelphia, May, 1936.
(13) Weaver, F. D., *J. Inst. Metals*, **56**, No. 1, 209 (1935).
(14) Williams, Thornton, "Rubber Plate Printing," Eighth Production Yearbook, N.Y., 1948, p. 178.
(15) U.S. Pat. 2,148,741 (Feb. 28, 1939), B. W. Gonser.
(16) U.S. Pat. 2,400,518 (May 21, 1946), F. W. Kreber, B. W. Gonser, and R. Schaffert.

J. HOMER WINKLER

TYROCIDINE. See *Antibiotics*, Vol. **2**, pp. 26, 31.

TYROSINE, $HOC_6H_4CH_2CH(NH_2)COOH$. See *Amino acids*, Vol. **1**, pp. 719, 726.

TYROTHRICIN. See *Antibiotics*, Vol. **2**, p. 13.

TYUYAMUNITE, $Ca(UO_2)_2(VO_4)_2.nH_2O$. See *Uranium*.

U

UCUHUBA BUTTER. See *Fats and fatty oils*, Vol. **6**, pp. 144, 147.

ULEXITE. See *Boron compounds*, Vol. **2**, p. 607.

ULTRAFILTRATION. See *Colloids*, Vol. **4**, p. 227.

ULTRAMARINE BLUES. See *Colors for foods, drugs, and cosmetics*, Vol. **4**, p. 313; *Pigments (inorganic)*, Vol. **10**, p. 649.

ULTRAMICROSCOPE. See *Colloids*, Vol. **4**, p. 228.

ULTRAPHOSPHATES. See *Phosphoric acids and phosphates*, Vol. **10**, p. 404.

ULTRASONICS

The acoustical spectrum may be divided into three regions on the basis of the limits of hearing of the human ear. The region from 20 to 20,000 cycles/sec. is generally referred to as the sonic, the region below 20 cycles/sec. is the infrasonic, and the region above 20,000 cycles/sec. the ultrasonic. Although the present discussion will involve ultrasonic waves, many of the more interesting effects and applications are not restricted to ultrasonic frequencies but extend into the sonic and even the infrasonic regions in some instances. This is not surprising since the classification of the acoustical spectrum into three regions on the basis of human hearing is somewhat arbitrary.

Some confusion exists concerning the term supersonic. The latter should be reserved for phenomena that occur with a velocity greater than that of sound in a particular medium. Thus, it is proper to refer to supersonic flight and, in contrast, ultrasonic frequencies.

The Generation of Ultrasonic Waves (1,2,9,11)

The various sound sources that are available for the generation of intense ultrasonic waves may be classified as flow devices and piston devices. **Flow devices** include *ultrasonic sirens and whistles* which are effective at frequencies below 10^5 cycles/sec. for producing relatively intense ultrasonic waves in gases. These ultrasonic sources represent simple extensions of similar devices used in the sonic range. In the majority of cases, the chemist is more concerned with the generation of intense ultrasonic waves in liquids rather than gases. The transfer of acoustical energy from a gas to a

liquid or solid is usually very small. A modified ultrasonic whistle (5), however, has been developed for use in liquids and is represented functionally in Figure 1. The impingement of the liquid stream from the restricted orifice with the sharp edge of the resonator produces a vibration of the resonator at its natural resonance frequency if the flow conditions are proper. Such whistles offer interesting possibilities for industrial processing, but they are not as well suited to laboratory work as the piston-type ultrasonic sources which are easier to control.

Two effects have proved particularly significant in terms of **piston-like** ultrasonic sources: the magnetostriction effect and the inverse piezoelectric effect. The *magnetostriction effect* as used for acoustical purposes involves the periodic expansion and contraction of a bar of metal such as nickel when placed in a magnetic field with an alternating magnetic component. The maximum vibration amplitudes are obtained when the frequency of the alternating component corresponds to a longitudinal resonance mode of the metal bar. Acoustical energy is propagated from the end of the

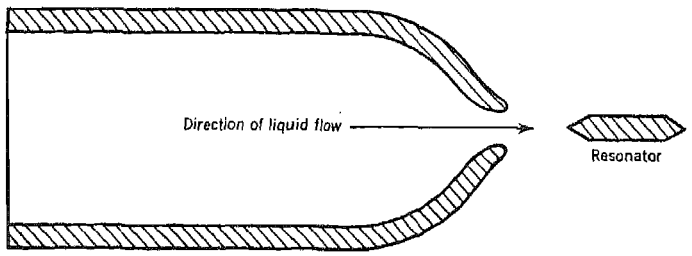


Fig. 1. Flow-type transducer for liquids (4,5).

metal bar into any medium in contact with it. One experimental arrangement employing this effect is shown in Figure 2. The ultrasonic waves are transmitted to the liquid through the metal diaphragm which is connected to one end of the nickel bar. Direct current with a superimposed alternating component is passed through the coil surrounding the bar.

Ultrasonic sources or transducers based on the *inverse piezoelectric effect* have found the most extensive use in both laboratory and industrial applications as of date. Single crystals of materials with anisotropic crystalline properties will expand or contract in an electric field, depending on the orientation of the electric field vector with respect to the crystal axes. If an a.c. electric field is involved, the single crystal will periodically expand and contract; hence, acoustical energy will be propagated into the surrounding medium. While the piezoelectric-type transducers have been used for generating ultrasonic waves in gases, the available intensities are low because of the relatively poor transfer of acoustical energy from the vibrating solid to the gas.

Figure 3 is a functional diagram of a piezoelectric ultrasonic source for work with liquids. α-Quartz is used in most cases for high acoustical intensities because of its relatively good mechanical properties. The most common geometric shape is a flat circular disk or plate with a diameter between 1 and 3 in. The thickness is determined by the frequency of the ultrasonic waves to be generated. The quartz plate must be driven electrically at a frequency corresponding to a thickness resonance mode if appreciable intensities are to be obtained. The electric field is applied by means of two conducting metal surfaces on the flat surfaces of the quartz plate. A radio-frequency generator is used as the source of the a.c. potential differences which are

developed between these two metal surfaces. In most instances an air space is used on one side of the quartz transducer in order to have virtually all of the acoustical energy propagated in one direction into the liquid.

Although quartz transducers are important in laboratory investigations involving ultrasonic waves, they are of limited significance in large-scale operations because of the relatively high cost and scarcity of large single crystals of α-quartz. See Vol. **12**, p. 331. In addition, there are serious restrictions in the geometric shapes that can be used, and the high a.c. voltages required to drive the quartz transducers often result in an electrical insulation problem.

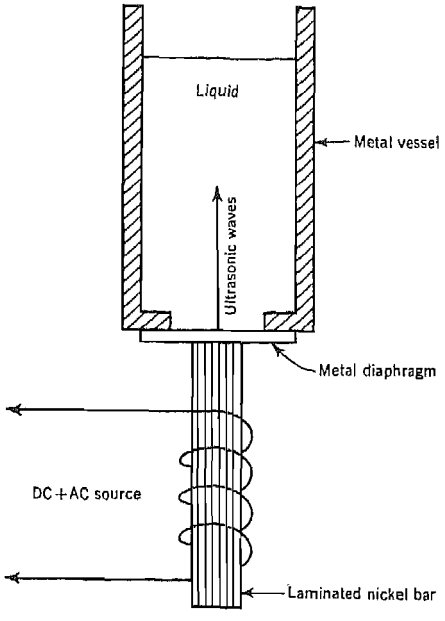


Fig. 2. Magnetostriction ultrasonic source.

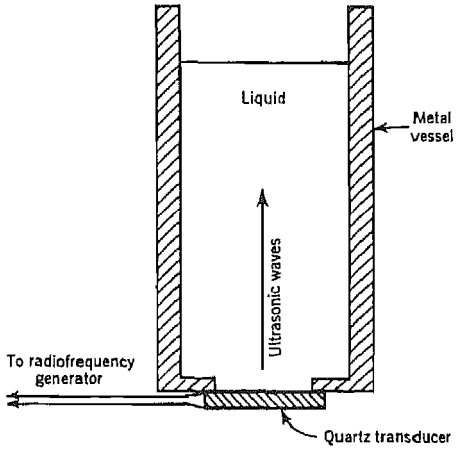
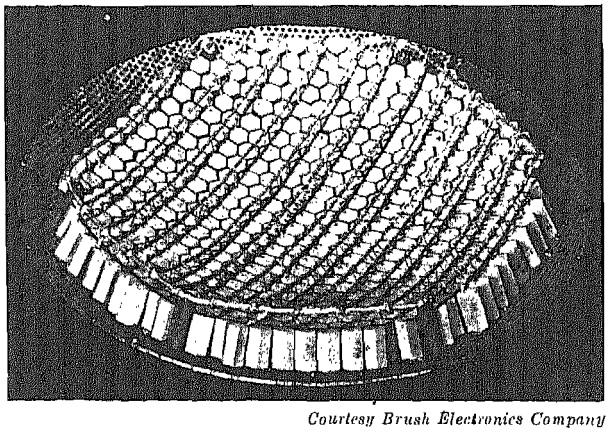


Fig. 3. Piezoelectric transducer.

In 1948, the ferroelectric material (2) barium titanate, $BaTiO_3$ (see *Titanium compounds*), became commercially available in a variety of forms suitable for the generation of ultrasonic waves. This material can be molded into any shape desired and fired in a furnace with suitable metal electrodes on the proper surfaces. Inasmuch as barium titanate is a ferroelectric, it can be subsequently polarized through relatively simple electrical and thermal procedures. Despite its polycrystalline nature, the polarized material can then be used for the production of ultrasonic waves in much the same way as the single crystal of α-quartz. The advantages of the barium titanate ceramic transducers are the lower cost, the much lower a.c. voltages required to drive them, and the diversified shapes in which they can be produced. With a bowl-type transducer, the ultrasonic waves converge at the center of curvature to provide a very high intensity at the focus. One hundred-fold increments or more in intensity are possible with this focusing action. With a cylindrical transducer a line focus is obtained. The inside and the outside surfaces of the cylindrical transducer are covered with conducting silver paint which serves as the electrode. This type of transducer can be installed in a pipeline and is particularly convenient for continuous

ultrasonic processing. When large barium titanate transducers are desired, a mosaic consisting of a number of small hexagonal pieces of the ceramic can be cemented together. This technique can be used to line the bottom of a tank or to form a very large concave transducer as shown in Figure 4. Electrical contact is made to each of the hexagonal elements through wires soldered to the top silver coverings and through the perforated metal plate upon which they are placed. The use of barium titanate ceramic in ultrasonic transducers represents an important development with respect to laboratory as well as industrial applications for ultrasonic waves.

The magnetostriction effect and the piezoelectric effects complement each other in regard to their use in acoustical transducers. The magnetostriction effect is used primarily for frequencies from 10^4 to 10^5 cycles/sec. At frequencies above 10^5 cycles/sec., the dimensions of the metal bars become prohibitively short and eddy current



Courtesy Brush Electronics Company

Fig. 4. Mosaic of hexagonal pieces of barium titanate (2).

losses are excessive even with laminated construction. The piezoelectric effect is used ordinarily for producing intense ultrasonic waves at frequencies above 10^5 cycles/sec. because the thickness of the elements becomes excessive below these frequencies. Cylindrical transducers of barium titanate, however, have been used to produce intense sound waves at frequencies well below 10^5 cycles/sec. Although quartz transducers have been used to produce ultrasonic waves at frequencies approaching 10^9 cycles/sec., it is difficult to obtain any appreciable intensity above 10^7 cycles/sec.

Physical Characteristics of Intense Ultrasonic Waves (1,8,11)

First-Order Characteristics. The propagation of acoustical waves through a medium involves periodic fluctuations in pressure, displacement, velocity, and acceleration of the particles constituting the medium. To a first-order approximation, these variations can be described by sine curves. On this basis, the amplitudes of these variations are listed in Table I for ultrasonic waves in water at a frequency of 10^6 cycles/sec. and an intensity of 1000 watts/sq.cm. which represents the highest generally available at present. Acoustical intensity represents the energy transmitted per unit time through a unit cross section perpendicular to the direction of propagation. The units are usually watts/sq.cm. Also in Table I for purposes of comparison are listed the corresponding quantities for air-borne sound at a frequency of 1000 cycles/

sec. and an intensity of 10^{-4} watt/sq.cm. The latter is substantially the highest sonic intensity encountered in everyday experience. The differences in the values for the various amplitudes in air and water in Table I not only reflect the differences in the frequencies, but also differences in the intensities and the acoustical impedances (velocity times density) of the mediums. For a given intensity, the displacement amplitude is inversely proportional to the frequency. The velocity and the pressure amplitudes are independent of the frequency, although dependent on the acoustical impedance of the medium. For a given frequency, the intensity is proportional to the square of any of the amplitudes. The far greater acceleration amplitude in comparison with the displacement amplitude for the ultrasonic waves supports the concept that ultrasonic waves represent virtually all acceleration and no motion. The maximum acceleration with these ultrasonic waves is equivalent to two million times that of gravity. Such accelerations prompt the question as to whether they are sufficient to rupture chemical bonds under favorable conditions such as in large polymer molecules. Unfortunately both experimental and theoretical evidence appear to indicate that these accelerations are insufficient insofar as ordinary chemical bonds are concerned. Relatively weak hydrogen bonds, however, can be disturbed as a consequence of these accelerations.

TABLE I. Comparison of First-Order Properties of Sonic and Ultrasonic Waves.

Properties	Sonic in air	Ultrasonic in water
Frequency	1 kc./sec.	1000 kc./sec.
Medium	Air	Water
Wave length	30 cm.	0.15 cm.
Intensity	10^{-4} watt/sq.cm.	10^{3} watts/sq.cm.
Displacement amplitude	1×10^{-3} cm.	6×10^{-6} cm.
Velocity amplitude	7 cm./sec.	4×10^{3} cm./sec.
Acceleration amplitude	4×10^{4} cm./sec.^{2}	2×10^{9} cm./sec.^{2}
Pressure amplitude	3×10^{2} dyne/sq.cm. or 3×10^{-4} atm.	6×10^{7} dynes/sq.cm. or 60 atm.

Although the pressure amplitude is surprisingly large (60 atm.), it does not pose any problem, provided the liquid is at a high static pressure. If ultrasonic waves at these intensities are introduced into a liquid at a static pressure of 1 atm., the question arises as to how the amplitude of the pressure variation may be 60 atm. When the liquid is free of suspended particles and dissolved permanent gases, tensions may actually occur in the liquid without the rupture of the liquid. Evidence is available from other studies that tensions of the order of 200 atm. or more may be developed in many liquids. In almost all cases, however, suspended particles such as dust particles and dissolved gas molecules serve as the nucleation centers for the rupture of the liquid. The latter is referred to as cavitation. When cavitation occurs, the sine curve is not even a crude approximation for the periodic variations associated with the acoustical waves.

The wave length of an acoustical wave is inversely proportional to the frequency; hence, ultrasonic waves have much shorter wave lengths than ordinary sound in the same medium. *As a result, ultrasonic waves are more directional and more readily focused.*

Secondary Characteristics (1,8,11). The secondary characteristics of ultrasonic waves for the most part are associated with deviations from sine-wave behavior in the

case of acoustical waves of finite amplitude. Typical of these secondary characteristics are *cavitation phenomena, radiation pressure effects,* and *thermal effects.* Cavitation is particularly important because many of the interesting physical and chemical effects of intense ultrasonic waves are directly associated with cavitation. The nucleation process required for the rupture of the liquid is not well understood at present. Apparently both suspended particles and dissolved gases are involved. Once the rupture occurs, however, the vapor of the liquid as well as dissolved gases in the liquid fill the cavitation bubble. As the pressure again builds up in the liquid surrounding the bubble during the compressional part of the cycle, the cavitation bubble at least partially collapses. The permanent gases that enter the bubble during the rarification part of the pressure cycle, however, do not completely redissolve during the compression, at least on a statistical basis. In the early stages, the cavitation bubbles are usually very small. With each cycle, more of the dissolved gases within the liquid enter the bubbles, and the cavitation bubbles increase until some critical size is reached, that is, until the radial resonance frequency corresponds to the frequency of the ultrasonic waves.

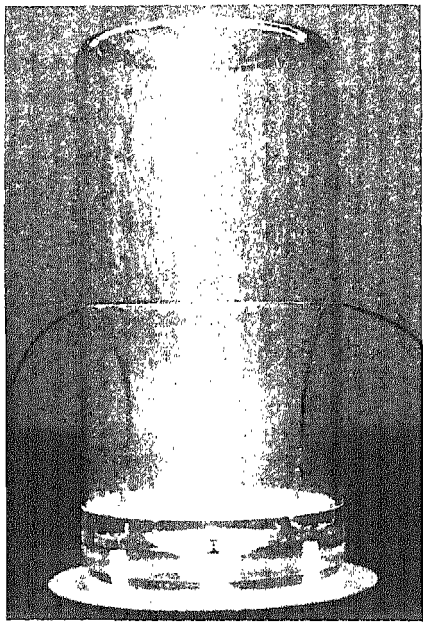


Fig. 5. Oil fountain produced by intense ultrasonic waves from a concave barium titanate transducer.

During the early stages when the cavitation bubbles contain primarily vapor and relatively little permanent gases, the partial collapse of the cavitation bubbles during the compressional part of the pressure cycle results in high instantaneous pressures within the bubble because of the inertia or momentum of the liquid. These instantaneous pressures are much higher than the pressure amplitudes referred to earlier and may be of the order of 10^3 atm. Such pressure changes in the collapsing cavitation bubbles are at least partially adiabatic, since the time periods may be of the order of microseconds or less. As a result, very high instantaneous temperatures may be realized within the cavitation bubbles. High instantaneous pressures of the order of 10^3 atm. may occur within a cavitation bubble when the bubble reaches a size such that its characteristic resonance frequency corresponds to the frequency of the ultrasonic waves. Large temperature rises are also associated with this resonance phenomenon. In both cases large local stresses occur in the liquid surrounding the cavitation bubbles.

In addition to the periodic properties associated with acoustical waves, there is a directional momentum, which manifests itself as a radiation pressure when the acoustical waves impinge on a phase boundary, or as a directional flow of the fluid in which the acoustical waves are absorbed. Radiation pressure and directional flow effects are very small with ordinary air-borne sound because of the low intensities. With the high intensities often encountered in work with ultrasonic waves, these effects become quite large. Figure 5 indicates the extent of these effects in terms of the fountain which forms when ultrasonic waves at a frequency of 600 kc./sec. from a concave

barium titanate transducer converge at the surface of the oil in the vessel. The radiation pressure is independent of the frequency and is directly proportional to the intensity. Acoustical intensities can be measured through the determination of radiation pressure.

If acoustical waves are absorbed in a medium, appreciable heating may occur. The absorption coefficient in most cases increases as the square of the frequency; hence, the thermal effects are much more pronounced with ultrasonic waves. In a liquid the progressive temperature rises within the liquid as a result of absorption should be distinguished from the large instantaneous temperature rises obtained within cavitation bubbles. The latter represent an unusual condition, since they are periodic and are realized for only very short periods of time, for example, fractions of microseconds. The progressive heating effects occur gradually and are usually undesirable. Adequate precautions ordinarily must be taken to cool any system that is being processed with high-intensity ultrasonic waves, particularly if the viscosity of the medium is high. One instance where these progressive heating effects have proved desirable is in therapeutic applications in which ultrasonic waves are used to produce heat within limited regions of the human body.

Applications in Chemistry

In addition to application in sonar and flaw detectors, there are applications of ultrasonic waves in chemistry which may be divided into three classifications: sonochemistry, the physical changes produced by ultrasonic waves, and the measurement of physical and chemical properties with ultrasonic waves. The term sonochemistry refers to the promoting of chemical reactions with ultrasonic waves and is somewhat analogous to the term photochemistry. Each classification will be discussed separately.

Sonochemistry (1,10a,12). Sonochemical reactions are dependent upon the formation of cavitation bubbles and are not observed in the absence of cavitation. The extreme conditions that exist within cavitation bubbles at various stages are sufficient to produce chemical activation of the various gases and vapors within the cavitation bubbles. This activation may be the result of the adiabatic temperature rises (see p. 412) or some electrification phenomenon associated with the formation of a nascent surface within the liquid. The specific mechanism has not been established definitely at present; both may be operative to some extent. It is interesting to note that sonoluminescence has been observed in liquids during ultrasonically produced cavitation.

Three of the most studied sonochemical reactions are the formation of hydrogen peroxide in water containing dissolved molecular oxygen, the formation of nitrous and nitric acids in water containing dissolved molecular nitrogen, and the formation of chlorine gas from carbon tetrachloride in water containing a dissolved inert gas. The details of these reactions have not been established despite considerable experimental work. In each case the active chemical intermediate is produced within the cavitation bubble. The threshold for cavitation in aqueous solutions containing dissolved gases may be as low as 0.03 watt/sq.cm. under ordinary conditions; hence, this is probably the threshold for sonochemical effects although appreciable rates of reaction are usually encountered only above 1 watt/sq.cm. Sonochemical reactions proceed slowly and are very inefficient with respect to the utilization of acoustical

energy. At the most only a few milliequivalents of reaction generally occur per 100 watt-hours of acoustical energy. Nevertheless, there is sufficient chlorine liberated from a few drops of carbon tetrachloride in water containing a dissolved gas to turn a potassium iodide–starch indicator solution blue within a second with moderately intense ultrasonic waves (for example, 10 watts/sq.cm.). The efficiency of the sonochemical decomposition of carbon tetrachloride correlates to some extent with the specific heat ratio as well as the thermal conductivity of the inert gas (for example, the helium-group gases, O_2, H_2, N_2) involved in the formation of the cavitation bubbles. Gases such as the nitrogen oxides and carbon dioxide which react with the solvent do not support the carbon tetrachloride reaction or similar sonochemical reactions.

Although quantitative measurements are not complete over any appreciable range of frequencies, these sonochemical reactions do not appear to have any significant frequency dependence in the range from 10 to 1,000 kc./sec. Cavitation is also relatively insensitive to frequency in this range. The rates of most sonochemical reactions decrease with increasing temperature, probably because of the temperature dependence of the cavitation processes, which are substantially rate-determining. Any increase in the vapor pressure of the solvent tends to decrease the maximum pressures that occur within either the collapsing cavitation bubbles or the resonating bubble. The static pressure in the system also influences the efficiency of sonochemical reactions. The yields generally pass through a maximum with increasing pressure, as would be anticipated on the basis of the dependence of ultrasonically induced cavitation on the static pressure. The maximum instantaneous pressures developed within the collapsing or resonating cavitation bubble should increase with increasing static pressure. The rate of formation of cavitation bubbles will decrease rapidly, however, after the static pressure increases above a certain value, since the tendency for a tension to be developed in the liquid will decrease.

Other chemical effects that have been reported for ultrasonic waves of appreciable intensity are: increases in the rates of reactions, including the hydrolysis of esters such as dimethyl sulfate and ethyl acetate; the hydration of acetylene to acetaldehyde; the decomposition of nitrogen-containing compounds such as benzoylazide and diazobenzene; the detonation of explosive such as nitrogen triiodide; and the oxidation of unsaturated oils. These reactions differ from those cited earlier in that they represent cases in which ultrasonic waves increase the rates of reactions that proceed even in the absence of ultrasonic waves. Some of these increments may be the result of the progressive heating within the systems because of the absorption of acoustical energy, although most workers have attempted to eliminate this possibility. Ultrasonic waves also increase the rates of reactions involving two or more phases by breaking up the concentration gradients at the interfaces (see p. 418).

Two other interesting sonochemical effects are the use of ultrasonic waves to promote polymerization as well as to produce degradation of polymers. Both sonic and ultrasonic waves decrease the induction period as well as increase the rate of polymerization by as much as twofold in the emulsion polymerization of styrene with a peroxysulfate catalyst. These effects can probably be explained in terms of the vigorous agitation and dispersive action associated with ultrasonically produced cavitation. Free radicals resulting from the extreme conditions within the cavitation bubbles may also be significant.

The degradation of polymers has been studied with molecules including polystyrene, nitrocellulose, proteins, rubber, and starch. In each case the polymer mole-

cules have been dissolved in a solvent. Degradation is most marked with large molecular weights, for example, 10^6; and should approach a limiting average value which represents approximately ¾ of the minimum chain length for rupture. According to the majority of the published work, ultrasonic degradation depends on cavitation and probably results because of the large local shear developed in the liquid in the vicinity of a resonating or collapsing cavitation bubble. Figure 6 shows the ultrasonic degradation of polystyrene dissolved in toluene as a function of time at a frequency of 400 kc./sec. and an intensity of 5 watts/sq.cm. As with other sonochemical effects, the degradation is not very dependent on frequency.

Sonochemical reactions are primarily of laboratory interest and are of relatively little significance with respect to industrial applications at present. Not only are the reactions very inefficient with respect to the acoustical energy involved, but in most

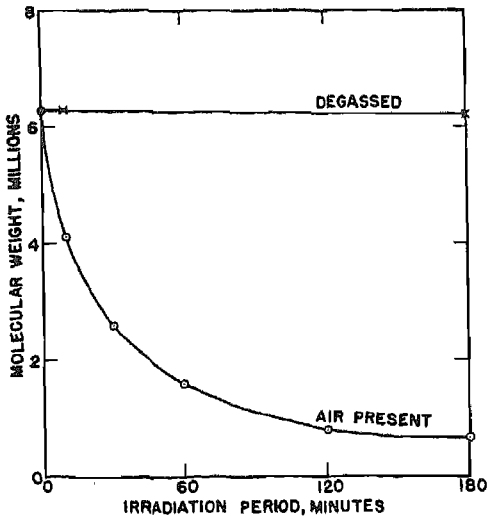


Fig. 6. Ultrasonic degradation of polystyrene in toluene (12).

instances the reactions are not of a useful nature. Possible exceptions to the latter are the degradation of proteins and the ultrasonic aging of alcoholic beverages.

Production of Physical Changes. The promise of ultrasonic waves with respect to applications in the chemical industry is in the physical changes that can be produced. Some of the more important physical changes are: the production of colloidal suspensions (1,10), the coagulation of suspensions (1,10), agitation effects (13), the degassing of liquids (1), and the effects on crystallization (1). Each will be discussed individually.

Ultrasonic waves can be used to produce fogs as well as suspensions of solids in liquids and emulsions. The fogs result whenever moderately intense ultrasonic waves are directed toward the surface of a liquid. The probable mechanism responsible for the fog formation is indicated in Figure 7. Surface vibrations or crispations are excited by the incident ultrasonic waves. As a result of the violence of these surface vibrations, the tops of the waves may actually break off to give rise to a fog. The reverse effect shown in Figure 7 also occurs, that is, small bubbles of air or gas are introduced into the liquid phase. Both effects may occur simultaneously. Surface vibrations and the mechanism represented in Figure 7 may also play an important part

in the formation of emulsions, such as mercury in water, which appear to proceed even in the absence of cavitation. The formation of most emulsions (for example, oil in water) as well as the production of suspensions of solids in liquids, however, has been found to be contingent on ultrasonically induced cavitation. The local stresses and violent disturbances that occur in the liquid in the vicinity of a resonating and/or collapsing cavitation bubble appear sufficient to produce these dispersions.

The formation of emulsions with ultrasonic waves proceeds sufficiently readily to offer industrial possibilities. Unfortunately, quantitative information is not available as to the efficiency of ultrasonic emulsification under various acoustical conditions. Electromagnetic sonic generators of 2-kw. output, however, have been used to homogenize milk at the rate of 250 gal./hr. The suspension of solids in liquids can also be

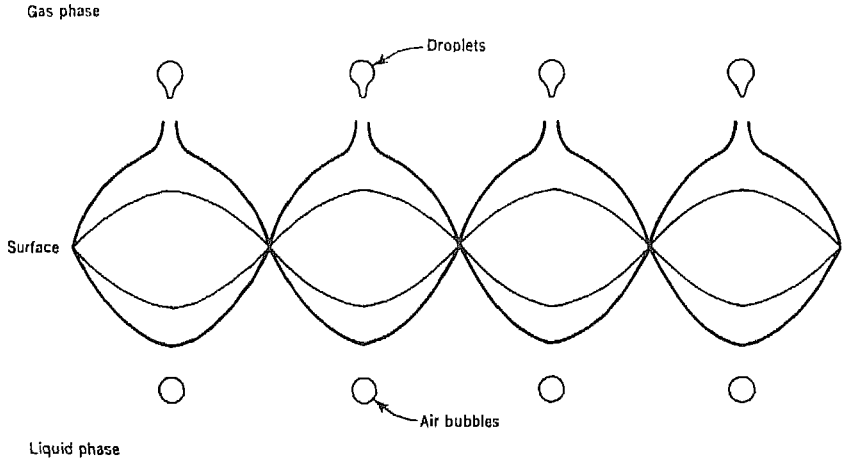


Fig. 7. Surface vibrations at a gas-liquid interface in the presence of acoustical waves (12a).

accomplished without too much difficulty if the high intensities of a focused ultrasonic source are available, particularly if the solid has been reduced to reasonably small particles before ultrasonic treatment. As in the case of other methods for preparing colloidal suspensions, some form of protection for the ultrasonically produced suspensions is usually necessary to ensure stability, since particle size is not the only factor. It is interesting to note that colloidal suspensions of metals in water can be produced by electrodepositing these metals in the presence of intense ultrasonic waves. The metal is not deposited on the cathode, but a colloidal suspension results.

At the same time that ultrasonic waves promote the formation of suspensions, there is an opposite tendency for an increased rate of coagulation. In the presence of cavitation, the dispersing action predominates in liquids. With relatively low acoustical intensities, the increased probability of collisions may produce an increase in the coagulation rate in systems which are unstable because of the lack of adequate protection for the particles. This increment is usually not more than two- or threefold, a factor that normally does not warrant the additional expense of the ultrasonic equipment. Even so, these increments in coagulation rates for particles suspended in liquids are larger than expected in terms of simple theoretical considerations. The latter are based on the fact that the differences in displacement amplitude as well as phase will occur between the various colloidal particles because of mass differences, the

lighter particles being displaced more than the heavy particles. The discrepancies between experimental results and predictions based on phase and amplitude differences in particle motion can at least in part be accounted for in terms of the second-order forces which cause macroscopic particles in the liquid to come together as if attracted to each other.

In the case of aerosols, acoustical waves are much more effective in promoting coagulation. The optimum frequency for producing coagulation through collision can be calculated for a given particle-size distribution on the basis of the amplitude and phase differences for particles of various sizes. In most instances this optimum frequency is sonic and often in the range 1,000–4,000 cycles/sec.

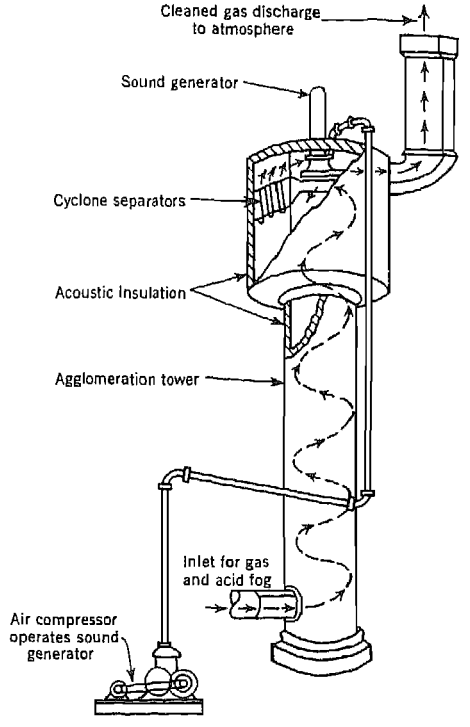


Fig. 8. Sonic precipitator for sulfuric acid mists (7).

The experimental coagulation rates are reasonable in terms of theory. The frequency of the acoustical waves, however, must be within narrow limits for a given particle-size distribution if the coagulation effects are to be pronounced. Furthermore, as the particles become larger during sonically induced agglomeration, the particle-size distribution shifts and the sound waves become relatively inefficient. Sonic techniques have been used for smoke precipitation. Figure 8 is a diagram (7) of a precipitator designed for sulfuric acid mists with a capacity of several thousand cubic feet per minute. The performance characteristics (3) for this type of precipitator are indicated in Figure 9. Units of comparable size have also been built for carbon black and sulfur fumes (3). The mist enters through the bottom and is subjected to the standing wave field from a siren operating at a frequency in the range 1,000–4,000 cycles/sec. and driven by a 10-hp. compressor. The mist particles increase to a size

of the order of 10^{-3} cm. in the sound field and are then removed with a cyclone-type precipitator as shown in the diagram. Water droplets are sprayed into the sound field in some cases in order to minimize the marked decrease in efficiency associated with changes in the particle-size distribution in the mist entering the precipitator. Although the initial cost for a sonic-type precipitator may be less than for an electrostatic precipitator, the operating costs are probably higher and the engineering problems more extensive. The sonic precipitator, however, may offer special advantages with particles that do not readily take on a charge, for example, molybdenum sulfide, and cases where there are possibilities of dust explosions. See also Vol. 7, p. 100.

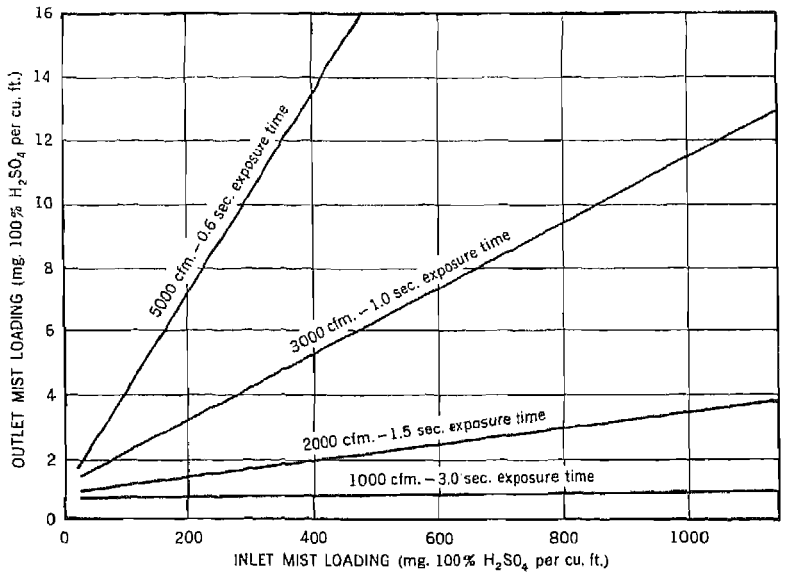


Fig. 9. Performance characteristics of a sonic precipitator (3).

Many physical and chemical processes involving two or more phases are limited by the concentration gradients that develop at the phase boundaries. For a liquid phase, ordinary mechanical agitation can be used to reduce the effective thickness of the concentration gradients to approximately 10^{-3} cm. but not much below this value because of the limitations normally involved in boundary layer problems. Ultrasonic waves at intensities sufficient to produce cavitation are capable of reducing the effective thickness of such concentration gradients in the liquid phase to values of the order of 10^{-4} cm. and possibly less. Much of this action is associated with the micro agitation in the liquid phase adjacent to any bubbles that are formed in the ultrasonic field through cavitation or otherwise. Such agitation effects result because of the vibrations or oscillations of the bubbles, as well as the high-velocity directional streaming of the liquid near bubbles in the sound field. In processes involving two fluid phases, surface vibrations of the type shown in Figure 7 are also important in reducing concentration gradients. Relatively low acoustical intensities are needed for the effective disruption of concentration gradients; hence, ultrasonic waves can be used to reduce such gradients without damaging solid surfaces through cavitation or producing any appreciable sonochemical changes. Increases in the rates of heterogeneous chemical reactions resulting from the disruption of concentration gradients

with ultrasonic waves are not classified as sonochemical effects since the mechanism is entirely physical and not chemical. Ultrasonic waves have been reported to produce considerable increments in the rates of heterogeneous processes in the following processes: dialysis, extraction, solution of solids in liquids, dyeing of fabrics, tanning of leather, pickling of metals, and electrodeposition of metals. The micro agitation associated with cavitation is now used on a commercial basis for the degreasing and cleaning of metal surfaces in chlorohydrocarbons. Ultrasonic waves are capable of cleaning metal parts with very irregular contours to an extent unattainable by other methods.

During ultrasonically produced cavitation in liquids, the dissolved permanent gases tend to come out of solution in small bubbles. This degassing effect is particularly rapid if the pressure above the liquid is reduced to some extent. Not only does this reduce the tendency for the gas to go back into solution, but also the growth of the bubbles in the ultrasonic field is more rapid. Degassing of liquids with reduced pressure in the absence of sound waves is a slow process because the diffusion of the dissolved gas molecules to the surface of the liquid proceeds at a very limited rate and the nucleation processes involved in the formation of gas bubbles within the liquid are also statistically slow unless the liquid is boiling. Ultrasonic waves increase the probability of nucleation because of the tendency for a tension to be developed in the liquid even at relatively low acoustical intensities; for example, the pressure amplitude is already 1 atm. for an acoustical intensity of 0.3 watt/sq.cm. in water. Surface vibrations, either at the upper surface of the liquid or at the surface of any bubble that may already have formed, also have been shown to give rise to tremendous numbers of additional gas bubbles which in turn promote the degassing of the liquid since nucleation is no longer a problem.

Ultrasonic waves seem promising as a means for degassing liquids such as molten metals and glasses with which it is difficult to use conventional techniques such as boiling. Ultrasonic degassing equipment is reported to have been built in Europe which is capable of degassing as much as 10,000 gallons of transformer oil per hour with 500 watts of electrical energy supplied to the barium titanate transducer. The unit operates at a reduced pressure to expedite the removal of the dissolved gases.

Ultrasonic waves promote the crystallization of materials such as sugar, whose solutions normally tend to supercool. The probability of nucleation is apparently increased appreciably with the propagation of the ultrasonic waves through the medium. Unfortunately there are insufficient experimental results available upon which to base any interpretation. The effect is reported to be in use on a commercial basis, however, for controlling crystallization with specialized organic compounds.

In addition to the physical effects described above, ultrasonic waves are used in the soldering of aluminum to remove the oxide layer through cavitation. Transverse ultrasonic waves are effective in cold-welding metals. Reciprocating drills operating at ultrasonic frequencies are also in use for drilling holes of irregular contour.

Measurement of Physical and Chemical Properties (1,6,8,11,13). The majority of the physical measurements with ultrasonic waves have involved the determinaton of the velocity and absorption of the acoustical waves. From such measurements it is possible to obtain information of both a macro and micro nature concerning the system. Typical of macro measurements are compressibility and viscosity and examples of micro measurements include information concerning the partitioning of energy within molecules and the study of the solvation of ions in solution.

Velocity measurements in gases and liquids are usually made with either an ultrasonic interferometer or pulse techniques. In the case of solids most of the ultrasonic velocity measurements have also been obtained with pulse techniques. With the acoustical interferometer, a standing wave is established within the fluid by means of a reflector and the velocity calculated from the wave length and the frequency. The wave length is usually determined by noting the variations in the alternating current through the piezoelectric transducer as the position of the acoustical reflector is varied. With the pulse technique the time required for the propagation of a short pulse consisting of a limited number of cycles of ultrasonic waves is determined by methods similar to those associated with radar. Under favorable conditions both methods are capable of accuracies of the order of $\pm 0.1\%$ for the velocity of ultrasonic waves. Velocity measurements are generally not frequency-dependent.

The adiabatic compressibility, β_S, and the isothermal compressibility, β_T, are related to the acoustical velocity, c, by the equations:

$$\beta_S = \beta_T/\gamma = 1/\rho c^2 \tag{1}$$

where ρ is the density and γ the ratio of the specific heats. Hence, the compressibility of the medium through which the ultrasonic waves are being transmitted can be determined readily from velocity measurements. In the case of gases, the isothermal compressibility can be computed from the equation of state and the specific heat ratio calculated from equation (1). Compressibility data have proved significant in terms of both inter- and intramolecular structure. Typical applications include the correlation of molal compressibilities and ultrasonic velocities with molecular volume, the measurement of ionic hydration, and the study of the changes in the structure of liquids produced by high pressures and temperatures.

Ultrasonic velocity measurements are also used to determine the elastic constants of solids. The acoustical velocities are related to the elastic constants for isotropic solids by the equation:

$$c_l = \left[\frac{E + (4/3)n}{\rho}\right]^{1/2} \tag{2}$$

for longitudinal waves and:

$$c_t = [n/\rho]^{1/2} \tag{3}$$

for transverse waves with c_l and c_t representing the longitudinal and transverse velocities, respectively, E the volume elasticity, and n the shear modulus.

The most direct methods for the measurements of ultrasonic absorption are based on the determination of the decrease in the amplitude of the ultrasonic waves after propagation through a known distance. Pulse techniques are used often since this eliminates some of the experimental problems associated with extraneous reflected waves from the walls of the container and affords an opportunity to measure velocity and absorption simultaneously. Absorption measurements in fluids can also be combined with velocity measurements with the acoustical interferometer. Both the pulse techniques and the interferometer are generally inadequate for absorption measurements in liquids at frequencies below 10^6 cycles/sec, because of the complications associated with diffraction effects in the acoustical field as well as the small value for the absorption. At relatively low ultrasonic frequencies, reverberation techniques have been used for the determination of adsorption coefficients in liquids. A pulse-

train of ultrasonic waves is introduced into a spherical or cylindrical vessel containing the liquid under investigation. The rate at which the amplitude of the ultrasonic waves decay is measured and the absorption coefficient calculated.

The absorption coefficient, α, for the acoustical amplitude is defined by the equation:

$$A = A_0 e^{-\alpha x} \tag{4}$$

where A_0 represents the amplitude of the acoustical waves at a given point and A the amplitude after the acoustical waves have been transmitted through a distance x through the medium. The coefficient α consists of two components: a viscous component and a thermal component. The viscous component is associated with frictional effects within the medium, while the thermal component arises because the compressions and rarifactions are not completely adiabatic. The former is the predominant component in acoustical absorption in most liquids, while the latter is the predominant component in gases. According to the classical treatments of absorption in terms of both contributing factors, the coefficient α should be directly proportional to the square of the frequency. In practice, departures are often encountered in liquids as well as in gases. In such cases, the absorption coefficient is abnormally high over a given range of frequencies. Thermal as well as structural relaxation effects are usually the explanation. Absorption studies in polyatomic gases provide information concerning the partitioning of energy among translational and internal degrees of freedom. The structural and relaxation effects responsible for the abnormal absorption in liquids, particularly solutions, are not completely understood, and in many instances not even identified. Structural relaxation effects have been identified in liquids containing long chain molecules, such as the polyisobutylenes, and also in the substituted cyclohexanes where the abnormal absorption has been correlated with the interaction of the ultrasonic waves with the equilibrium between the chair forms. Absorption measurements have also been used to study the kinetics of very fast reactions with half lives of 10^{-4} sec. or less.

The absorption and scattering of ultrasonic waves have been used for such practical applications as following the setting of cement, determining the consistency of wood pulp, and checking the characteristics of rubber.

Ultrasonic equipment is available commercially for the measurement of the viscosity of Newtonian liquids (see *Viscometry*). With non-Newtonian liquids, an effective value is obtained. The ultrasonic viscometers measure the damping effect that the liquid has on a small vibrating bar. The electrical equipment can be calibrated to read directly the product of the viscosity and density. The advantages associated with ultrasonic viscometers are that measurements are made continuously and that only a few cubic centimeters of sample are required.

Bibliography

(1) Bergmann, L., *Der Ultraschall und seine Anwendung in Wissenschaft und Technik*, 6th ed., S. Hirzel Verlag, Stuttgart, 1954 (5160 references).
(2) Butterworth, J. W., *Chem. Eng. Progress Symposium Series*, **47**, No. 1, 69–76 (1951).
(3) Danser, H. W., *Chem. Eng.*, **57**, No. 5, 158–60 (1950).
(4) Hiedeman, E. A., *Chem. Eng. Progress Symposium Series*, **47**, No. 1, 51–56 (1951).
(4a) Hueter, T. F., and Bolt, R. H., *Sonics: Techniques for Industrial Uses of Sound and Ultrasound*, Wiley, N. Y., 1955.
(5) Janovski, W., and Pohlman, R., *Z. angew. Physik*, **1**, 222 (1948).
(6) Markham, J., Beyer, R., and Lindsay, R., *Rev. Mod. Phys.*, **23**, 353–411 (1951).
(7) Nord, M., *Chem. Eng.*, **57**, No. 10, 116–19 (1950).

(8) Richardson, E. G., *Ultrasonic Physics*, Elsevier, N.Y., 1952.
(9) Samsel, R. W., *Chem. Eng. Progress Symposium Series*, **47**, No. 1, 77–84 (1951).
(10) Sollner, K., "Sonic and Ultrasonic Waves in Colloid Chemistry," in Alexander, *Colloid Chemistry—Theoretical and Applied*, Reinhold, N.Y., 1944, Vol. V, pp. 337–73.
(10a) Uglietti, G. A., *Gli Ultrasuoni*, Ulrico Hoepli, Milan, 1952.
(11) Vigoureux, P., *Ultrasonics*, Wiley, N.Y., 1951.
(12) Weissler, A., *J. Acoust. Soc. Am.*, **25**, 268–94 (1953).
(12a) Willard, G., paper presented at the National Meeting of the Acoustical Soc. of America, New York, June 1954.
(13) Yeager, E., and Hovorka, F., *J. Acoust. Soc. Am.*, **25**, 443–55 (1953).

ERNEST YEAGER AND FRANK HOVORKA

UMBER. See *Pigments (inorganic)*, Vol. **10**, p. 637.

γ-UNDECALACTONE, $CH_3(CH_2)_6CH.CH_2.CH_2.CO.O$. See *Perfumes (synthetic and isolates)*, Vol. **10**, pp. 26, 32.

***n*-UNDECANE,** $CH_3(CH_2)_9CH_3$. See *Hydrocarbons*, Vol. **7**, p. 604.

***n*-UNDECYL ALCOHOL,** $CH_3(CH_2)_9CH_2OH$; ***n*-UNDECYLENYL ALCOHOL,** $CH_2{:}CH(CH_2)_8CH_2OH$. See *Perfumes (synthetics and isolates)*, Vol. **10**, pp. 17, 28.

***n*-UNDECYL ALDEHYDE,** $CH_3(CH_2)_9CHO$; ***n*-UNDECYLENYL ALDEHYDE,** $CH_2{:}CH(CH_2)_8CHO$. See *Perfumes (synthetics and isolates)*, Vol. **10**, pp. 20, 29.

10-UNDECYLENIC ACID, 10-UNDECENOIC ACID, $CH_2{:}CH(CH_2)_8COOH$. See *Fatty acids*, Vol. **6**, pp. 175, 266.

***n*-UNDECYLIC ACID, UNDECANOIC ACID,** $CH_3(CH_2)_9COOH$. See *Fatty acids* Vol. **6**, pp. 174, 250.

UNIONS. See *Pipes and valves*, Vol. **10**, p. 721.

UNIT OPERATIONS AND UNIT PROCESSES

From an overall viewpoint, manufacturing in the chemical industry can be resolved into a coordinated sequence of unit operations and unit processes. The *unit operations* refer to the *physical* changes such as absorption, adsorption, drying, fluid mechanics (fluid flow), heat transfer, evaporation, distillation, extraction, crystallization, mixing and agitating, and size conditioning. The *unit processes* pertain to the *chemical* changes such as alkylation, amination by reduction, ammonolysis, halogenation, hydrogenation, hydrolysis, ion exchange, nitration, oxidation, and sulfonation. No distinction is made in the chemical changes between whether they are in the field of inorganic or organic chemistry.

Chemical engineering grew out of chemistry as electrical engineering had similarly earlier grown out of physics. There were, however, a number of new and distinct concepts which were never a part of chemistry. These were largely the *physical changes* or *unit operations*. Although these were not so named until very much later, the first written description of these unit physical changes was embodied in the book by Davis (2), who gave a series of lectures in the Manchester Technical School in England in 1887. However, the matter rested in England with the publication of this book and was not pursued further at that time.

In 1903 William H. Walker went to the Massachusetts Institute of Technology

as Professor of Chemical Engineering and conceived the breaking down of the physical changes employed in what at that time was called industrial chemistry into units such as filtration, centrifugation, and heat transfer. Dr. Arthur D. Little, who had been in a consulting partnership with Dr. Walker, suggested the name unit operations in 1915. The initial development of this concept was carried through by a group of professors at the Massachusetts Institute of Technology, and led to the publication, in 1923, of *Principles of Chemical Engineering*, by W. H. Walker, W. K. Lewis, and W. H. McAdams. This was revised in 1937 with Gilliland as the fourth author (9). The newest summary in book form of the vast amount of work done on unit operations is in reference (1). Most of the unit operations are reviewed annually in the January number of *Industrial and Engineering Chemistry*.

After seeing the success of the unitary study of physical change, many chemical engineers started to place greater emphasis on the unitary features of *chemical* change, especially on those aspects which would affect chemical economics. In 1928 Groggins used the earliest recorded association of the term *unit processes* with the field of chemical activity (4). In the fall of 1930, in the Chemical Engineering School of Purdue University, R. Norris Shreve started giving courses classified by the chemical change. The unit process classification was further formalized by the book edited by Groggins (3), with the first edition published in 1934. Keyes in 1934 stated: "Up to the present most stress has been laid on the chemical engineering unit operations which consist entirely of physical transformations such as distillation, evaporation, crushing, grinding, filtration, etc. Recently, I have called attention to the chemical engineering unit processes which involve changes in chemical composition, for example, oxidation, reduction, hydrolysis, and esterification. Little is known, at the present time, about the fundamental principles of unit processes, whereas considerable has been learned in recent years about the less complicated principles of unit operations. This is probably the reason that stress has been laid on unit operations rather than the more significant 'chemical engineering unit processes' " (6).

The Division of Industrial and Engineering Chemistry of the American Chemical Society has long fostered papers in this field as the Unit Process Symposia, which are now being embodied in a permanent Subdivision on Chemical Processes, with the expectation of having this as an annual feature of the fall meeting of the American Chemical Society. The literature covering the unit processes is abstracted annually in the September number of *Industrial and Engineering Chemistry*.

In both unit operations and unit processes the similarities within any unit operation or unit process are separated and studied, thus drawing attention to the like qualities of a given physical change, as in distillation, or of a given chemical change, as in hydrogenation. The emphasis thus placed upon the similarities led to unifying theories and to expression by rules and formulas of these like aspects, and these, in turn, led to a clearer understanding of the function, and thus to improved design of the necessary equipment. This is the scientific and engineering approach. The ultimate study by this method of the technical changes culminated in chemical engineering formulas and laws for using the classified observations in each unit operation or unit process. These formulas and laws are the tools the chemical engineer employs in designing or operating a distillation column or a hydrogenator.

The result of this study by chemical engineers both in universities and in industry has been exceedingly helpful. By the correlation and formulation of data both for the unit physical operations and the unit chemical processes, engineering calculations

can be made in many cases for exact design and performance of many steps in the manufacture of chemicals. In the unit operations field, the formulation has been most successful, particularly in heat transfer, distillation, and fluid flow, although in some of the operations, such as crystallization, mixing, and perhaps filtration the results are not yet as useful. In the unit process field, chiefly because of the complexity of the underlying variables, the formulation has been much less exact and very much less extensive.

To an increasing extent one finds in different chemical plants a factory segregation according to the unit processes or operations. A building or a part of the plant may be set apart to carry on nitrations, hydrogenations, alkylations, or fermentations; on the other hand, a building may be devoted to distillation or pumping (fluid flow). The close relationship occasioned by factory segregation brings together like equipment. This segregation and similarity in equipment leads more easily to multiple use of equipment. The aim of the plant manager is, of course, to employ a given piece of equipment year in and year out for the same chemical, but frequently markets vary and the same piece of equipment may be more economically used at one time for halogenation of a given chemical and later for halogenation of another raw material. This is also true in distillation. One column will be employed year in and year out for the same operation, but may be used at one time for alcohol and another time for rectification of acetone.

Above anything else, the classification and arrangement under the unitary concept enables the chemical engineer to design and plan on the basis of group performance. In this way basic principles pertaining to an entirely similar group of chemical reactions and of physical changes are emphasized rather than the specific details of individual performance. These specific details enter more into a modification of the group conditions. Past knowledge with other members of a group helps greatly in the handling of the manufacture of a new chemical within this same group and at higher conversion and yields with consequent lower costs.

In classifying and naming these units of the chemical engineer, the tendency has been to turn to the more fundamental similarities wherever possible. This has been easier to do for the unit operation because conditions are simpler. In the following outline, the principal unit operations are arranged under subheadings of energy transfer and mass transfer. Although some of the unit operations involve both energy transfer and mass transfer, the respective unit operation was placed under whichever one seemed to be the more important. An attempt has been made to point out in this outline that many of these have been considered the reverse of another unit operation.

Principal Unit Operations

Energy Transfer

(A) Mechanical energy transfer
1. Size reduction (crushing and grinding)—agglomeration (flocculating, sintering, pelleting)
2. Size separation; gravity separation

(B) Heat energy transfer
3. Heating—cooling
4. Evaporation—evaporative cooling

Mass Transfer

(A) Bulk mass transfer
5. Transportation of fluids (fluid flow)

6. Materials handling (transportation or storage)
7. Classification or sedimentation of solids—fluidization
8. Flotation
9. Filtration (fluid flow through porous media)
10. Centrifugation
11. Mixing—separation (sedimentation)

(B) Molecular mass transfer

12. Distillation
13. Extraction or leaching—crystallization
14. Absorption of gases—desorption
15. Gas diffusion
16. Drying—adsorption on solid

Although the overall fundamentals of unit processes are largely concerned with anything that increases the kinetics, conversion or yield, and although these fundamentals pertain to all the unit processes, there is more diversification between the different individual members of this division than is true of the unit operations. Therefore, in naming them, it is difficult to have subclassifications, although it may be noted that some of the entries in the following list are related to others in various ways, for example, combustion could be considered as a special case of oxidation, and condensation in many cases results in polymerization. The Friedel-Crafts reaction is sometimes listed as a unit process, but since it specifies a particular type of catalyst, rather than a type of reaction, it has been omitted in the following list, being subsumed under alkylation and condensation.

Principal Unit Processes

1. Combustion
2. Oxidation
3. Neutralization
4. Silicate formation
5. Causticization
6. Double decomposition
7. Calcination
8. Dehydration
9. Nitration
10. Esterification
11. Reduction
12. Ammonolysis
13. Halogenation
14. Sulfonation
15. Hydrolysis and hydration (saponification, alkali fusion)
16. Hydrogenation, dehydrogenation and hydrogenolysis
17. Alkylation
18. Condensation
19. Polymerization
20. Diazotization and coupling
21. Fermentation
22. Pyrolysis or cracking
23. Aromatization
24. Isomerization
25. Acylation
26. Hydroformylation (oxo process)
27. Ion exchange

Both unit operation and unit processes are, of course, important in any chemical manufacture, but it may be noted that frequently more money can be saved in the manufacture of a given chemical by increasing the conversion and the yield, that is, by improving a unit process, than from improvement in a unit operation. This is because in the making of chemicals, the raw materials, amounting to between 50 and 75%, are an important part of the total manufacturing expense.

Stress should be placed upon the fact that although these unitary aspects of chemical engineering have been of value for research and development as well as design, in the actual manufacture of a chemical one does not usually find an isolated case of a unit physical change or a unit chemical change taking place by itself. In most cases,

the chemical change at least is associated with a physical change, for instance, when the nitration change takes place with the evolution of heat (heat transfer) under agitation (mixing). Indeed, although the object of separation into these units has brought forth principles, formulas, and much progress, actually the industrial integration of these changes occurs to a marked extent. With the increasing importance of continuous rather than batch processing, this integration has become more marked. Continuous processing, which was early adopted in the alkali and sulfuric acid industries, has become a characteristic of the petroleum industry and is rapidly spreading to other large scale chemical manufacturing.

The coordination of the unit physical operations and the unit chemical processes of an industrial process is expressed in flow sheets (see, for example, Vol. **1**, p. 541). The changes required to transform the raw materials into chemical products are arranged schematically, and this greatly facilitates a clear visualization of the interrelations of the equipment required.

In conclusion it may be stated that the unitary concept, as applied to both physical and chemical changes, has been useful and has emphasized the fundamental systems and principles rather than the technical details.

Bibliography

(1) Brown, G. G., *et al.*, *Unit Operations*, Wiley, N.Y., 1950.
(2) Davis, G. E., *Handbook of Chemical Engineering*, Davis Brothers, Manchester, 1904.
(3) Groggins, P. H., 4th ed., *Unit Processes in Organic Synthesis*, McGraw-Hill, N.Y., 1952.
(4) Groggins, P. H., *Chem. & Met. Eng.*, **35**, 466 (1928).
(5) Hougen, O. A., and Watson, K. M., *Chemical Process Principles*, Wiley, N.Y., 1947.
(6) Keyes, D. B., *Chem. & Met. Eng.*, **41**, 244 (1934).
(7) Perry, J. H., *Chemical Engineers' Handbook*, 3rd ed., 1950.
(8) Shreve, R. N., *Chemical Process Industries*, 2nd ed., N.Y., 1955.
(9) Walker, W. H., Lewis, W. K., McAdams, W. H., and Gilliland, E. R., 3rd ed., *Principles of Chemical Engineering*, McGraw-Hill, N.Y., 1937.

R. NORRIS SHREVE

UNITS AND THEIR SYMBOLS

Since measurement is fundamental to science, accurate designation of the units of measurement is essential. The units most used in scientific work, the world over, are based on the centimeter, the gram, the second, and the Centigrade degree. The basic standards for the first two of these are the standard meter and the standard kilogram, which are kept in Paris. In the English-speaking countries some scientists, and most engineers, use the foot-pound-second system, with degrees Fahrenheit.

There is a tendency to change from the use of particular objects as fundamental standards to fundamental physical constants, such as the wave length of the line at 5461 A. of mercury-198 as the unit for length.

This article deals with the symbols used to represent the fundamental units, and the measurable quantities derived with their use. The physical chemist and the chemical engineer frequently deal with measurable quantities of great variety and complexity—work, energy, entropy, concentration, temperature gradient of viscosity. The list is long and it grows. To represent all these quantities by univocal symbols taxes the resources of two fonts of the Roman and Greek alphabets;

indeed, for certain mathematical expressions Hebrew characters have to be pressed into service. In the choice of symbols it is highly desirable to have as much systematization as possible, not only to facilitate communication among scientists, but because even in one man's work confusion arises easily unless great care is taken to keep the meanings of symbols distinct. Examples of possible confusion are the use of H for enthalpy, height, magnetic field intensity, and humidity, and the use of G to designate Gibbs free energy in Europe and by chemical engineers in this country, whereas other scientists in the U.S. use F for the same thermodynamic magnitude. When this is done, then F for the Faraday constant (which often occurs in the same mathematical equation) must be distinguished by a bar over it, or by the use of a Gothic capital letter.

The standardization of symbols of special interest to the chemist and chemical engineer has received considerable attention both in this country and elsewhere. Some of the organizations interested in this kind of work and in the efforts for cooperation will be discussed below. The development of agencies which have standardization as their sole purpose has helped immeasurably in scientific and industrial progress.

There are a few simple rules for the selection of symbols for units. The American Standards Association requires that all primary symbols be single characters with subscripts used when distinctions are necessary. Symbols for quantities constituting a well-defined class should belong to the same alphabet, font, and case, which should be such as to permit modification in accordance with a uniform scheme for the representation of any important series of corresponding derived quantities. Avoidance of departure from the standard practice of mathematicians regarding the use of signs, operator symbols, and the like is sought. In standardizing work past custom is widely kept in mind.

It is convenient in many cases to use a symbol having some obvious relation to the word for the quantity symbolized, as V or v for volume, P or p for pressure. Often, however, this leads to individual symbols with more than one meaning, since, for example, V or v is also convenient for velocity. The meaning may be clear from the context, but ambiguities must be avoided, and awkward constructions minimized. Alternative symbols are needed, and provided. Thus velocity in general can be represented by u. It is customary to use T for absolute temperature (either Kelvin, that is, Centigrade units, or Rankine, Fahrenheit units) and t for temperature measured from the arbitrary zeros of the Centigrade or Fahrenheit scales; if, then, time is also to be represented, the Greek letter τ (tau) can be used.

Symbols of the kind under discussion (if from the Latin alphabet) are usually printed in italic letters (designated on the manuscript by a straight underline) and there is no period after the symbol. Symbols are not abbreviations in the strict word-abbreviation sense. The use of italic letters in printing is helpful both in distinguishing symbols or combinations thereof from word abbreviations (now often used without following periods) and also in distinguishing the symbols from single-letter words.

Graphical symbols for diagrams, flow sheets, and the like have been separately standardized. A few pamphlets giving this kind of information of interest to the chemical engineer are listed under "Sources of Information" below.

Organizations

Many organizations have taken an interest in the standardization of units and symbols. Some of these are national and some are international. Within nations

both governmental agencies and civilian groups representing various branches of science and technology have been more or less active. In comparatively recent years most of this kind of work has been centered in such national organizations as the American Standards Association (ASA), founded in 1918 and devoted to the single purpose of standardization, or in its international equivalent, the International Organization for Standardization (ISO).

The American Chemical Society has done, or assisted in, considerable standardizing work relating to such subjects as reagents, analytical methods, atomic weights, and chemical nomenclature (the naming of compounds in particular), and it has appointed unofficial representatives on ASA standardizing committees, but the Society has done only a little direct work on unit and symbol standardization. The Society has taken action on its own in certain emergencies, as when microchemistry was rapidly developing.

The American Institute of Chemical Engineers has done active work on symbols for chemical engineering. Since 1932 it has had a standing committee at work on a System of Symbols and Nomenclature of Chemical Engineering, which made a report in 1946. The work was done in cooperation with ASA and there is an available pamphlet (ASA Z10.12-1946) entitled "Letter Symbols for Chemical Engineering" (see p. 430). Four other engineering societies and the American Association for the Advancement of Science were additional sponsoring organizations. This standard is under active revision, with publication of the revised list expected soon. In work of this sort done primarily by an organization like the American Institute of Chemical Engineers in cooperation with ASA, committees both of the initiating organization and ASA often have identical membership, as in this case.

After a joint committee of The Chemical Society, The Faraday Society, and The Physical Society in England had in 1937 issued a "Report on Symbols for Thermodynamical and Physicochemical Quantities and Conventions Relating to Their Use" the Royal Society set up (in 1938) a Standing Committee on Symbols, on which the above Societies were represented, to consider from time to time any direction in which the 1937 standard list should be revised. A revision appeared in 1951; this is a good example of cooperation between chemists and physicists in this kind of work. The British Standards Institution, in its functions much like ASA in America, has now used this 1951 pamphlet as the basis for a somewhat more comprehensive document to be used in British publications in general. It is known as British Standard 1991 (see p. 431). There is evidence that these standards are being used widely.

A number of organizations both in the U.S. and abroad could be listed as having made efforts for the standardization of units and symbols relating to more or less specific fields of interest. The work of the American Association of Physics Teachers would serve as an example. The U.S. National Research Council has had committees. Some idea of the results obtained by certain of these groups (results of most current interest to American chemists and chemical engineers) can be learned from the lists of sources of information given below.

Nations usually have governmental bureaus or departments devoted to standards. Customarily there is close cooperation, or at least no conflict, as far as the work of standardization associations and other groups are concerned. As far as its direct interest in units is concerned the U.S. Bureau of Standards is endeavoring to define fundamental constants, such as the units of light, heat, length, and weight, in terms of critical constants of nature rather than as related to destructible standards, and as a

second concept of a proper activity the Bureau is endeavoring to make more precise determinations, and thus to increase the number of significant figures in the determined values.

Incidentally mention is made that governments, as well as standardizing associations, with the help of specific industries and industrial organizations, do much work in the way of standardizing raw materials, commodities, equipment, testing methods, safety measures, and the like, in addition to the kind of standardization primarily discussed here. Government and other standard specifications are extremely numerous. ASA has a Chemical Industry Advisory Board and a Chemical Industry Correlating Committee of relatively recent creation (1949).

The coordination of national standards rather than the creation of international standards has usually been the objective of international standardizing organizations. Fundamental units have been standardized on an international basis for the most part. The first International Conference on Weights and Measures was held in Paris in 1875 and seventeen of the nineteen attending nations signed a convention for the establishment of a permanent International Bureau of Weights and Measures with headquarters near Paris. The latest international conference of this general significance was the Second Triennial Plenary Session of ISO held in New York, N.Y., in 1952.

The International Federation of National Standards Associations (founded in 1926), whose work stopped during World War II (in 1939), was commonly known as ISA. The new international organization which followed it, namely the International Organization for Standardization, is known as ISO (rather than IOS), apparently to change the ISA "symbol" as little as possible. ISO emphasizes that its purpose is the coordination of national standards, not the creation of international standards; this approach is said to be essential to progress. ISO has over thirty member countries and seventy-seven technical committees are at work. The Dansk Standardiseringsråd, Vesterbrogade 1, Copenhagen V, Denmark, has the secretariat for units and symbols; it heads up a Technical Committee known as ISO/TC12—Quantities, Units, Symbols, Conversion Factors and Conversion Tables.

Agencies primarily in the standardizing business have the working knowledge, organization, and machinery for gaining cooperative agreement and for making the results generally available. Accordingly, it has become increasingly realized in scientific and technical organizations in this country that it is wise to work with such national organizations as ASA and the American Society for Testing Materials (ASTM). These organizations, ASA in particular as far as standard units and symbols are concerned, are doing important, useful work. A common practice is to apply the principle of overlapping membership in creating committees of such organizations as ASA and ASTM, committee members in sponsoring or cooperating organizations being made members of the committees of the standardizing organization.

ASA is a federation of more than a hundred technical societies, trade and business associations, professional organizations, and consumer groups. Well over two thousand individual American companies have company memberships.

The purposes of ASA are to provide systematic means by which organizations concerned with standardization can cooperate in establishing American standards, to stimulate standardization work, to serve as a clearing house for information on standardization, to further the standardization movement as a means of advancing national economy and of promoting knowledge and use of approved standards, and to act as the

authoritative American channel in international cooperation in standardization work. In furtherance of its purposes ASA maintains space for meetings of committees of sponsoring organizations, keeps up the Library of Standards, publishes a journal (the *Magazine of Standards*, formerly known as *Industrial Standardization*), and at a nominal charge distributes many printed pamphlets which disclose the results of standardization work. The ASA Library of Standards maintains a complete set of the standards of other countries.

ASA is a very useful organization to all kinds of groups interested in standardization whether they be industrial, as manufacturers, investigators in science and technology, other users of standard information, or consumers of standardized commodities.

ASTM very closely follows units and symbols recommended by ASA.

While ISO now plays a leading role in international standardization, mention should be made of the fact that there have been Pan-American standardization conferences, and other more widely international efforts for standardization have often been made. The International Union of Pure and Applied Chemistry has a Commission on Physico-Chemical Symbols and the Coordination of Scientific Terminologies. It has worked on certain specific units and symbols at times and it has issued a general report on these subjects. Although the United Nations Educational, Scientific, and Cultural Organization (UNESCO) has done no direct work on the standardization of units and symbols, it has manifested its interest in this subject by transmitting problems to ISO for reference to the appropriate technical committees of that body while "intimating that UNESCO attaches importance to this matter, offers any cooperation in its power, and desires to follow developments."

"Enforcement" is perhaps too strong a word to apply with reference to any standard. At least the well-nigh universal practice is for standards to be reached by common consent and usually to be followed because of recognized merit in such agreement. Certainly this is true of standard units and symbols. Economy is served by many standards and this stimulates their use. Some individualists have preferences and some individuals are careless. Perhaps the nearest to enforcement of unit and symbol standards is the action of the editors of scientific and technical journals in trying to maintain standards between their covers.

Sources of Information

Instead of the usual bibliographic list of references, here is a more informal, semi-classified list of sources of information.

1. For *general as well as specific information* concerning standardization, write the American Standards Association, 70 East Forty-fifth Street, New York 17, New York. This organization is the American representative of ISO so that it is a source of standardization information of an international nature as well as of a national nature. ASA distributes many *standardization pamphlets* at a nominal price. A 30-page Price List is available. Those pamphlets relating to units and symbols of special interest to the chemist follow:

   Z10.12-1946: Letter Symbols for Chemical Engineering
   Z10.4 -1943: Letter Symbols for Heat and Thermodynamics Including Heat Flow
   Z10.6 -1948: Letter Symbols for Physics
   Z10.2 -1942: Letter Symbols for Hydraulics
   Z10.3 -1948: Letter Symbols for Mechanics of Solid Bodies
   Z10.10-1953: Letter Symbols for Meteorology
   Z10.5 -1949: Letter Symbols for Electrical Quantities
   Z10f -1928: Mathematical Symbols

Z32.2.3-1949: Graphical Symbols for Pipe Fittings, Valves and Piping
Z32.2.4-1949: Graphical Heating, Ventilating, and Air-Conditioning Symbols for Use on Drawings
Z32.2.6-1950: Graphical Heat-Power Apparatus Symbols
Z32.2.1-1949: Graphical Welding Symbols

2. For *news* concerning standards, see the *Magazine of Standards*, published by ASA. This is now in its 25th volume.
3. For a good, concise discussion of the *fundamental units* and their significance see "Units, dimensions of" in the *Encyclopaedia Britannica*.
4. For *current information* on newly suggested units, names, and (or) symbols of interest to the chemist, see the headings *Units* and *Symbols* in the Subject Indexes to *Chemical Abstracts*.
5. If, *while writing a paper*, help is needed concerning units, symbols, word abbreviations, and the like, useful pamphlets can often be obtained from the editor to whose journal a paper is to be submitted.
   (*a*) The American Institute of Physics publishes a 28-page Style Manual which is followed by:
   The Physical Review
   Reviews of Modern Physics
   Journal of the Optical Society of America
   The Journal of the Acoustical Society of America
   American Journal of Physics
   The Review of Scientific Instruments
   The Journal of Chemical Physics
   Journal of Applied Physics
   Physics Today
   Noise Control
   Copies can be obtained for $1.00 sent to American Institute of Physics, 57 East Fifty-fifth Street, New York 22, N.Y.
   (*b*) The 46-page booklet entitled "Directions for Abstractors and Section Editors of *Chemical Abstracts*" contains like information. "Directions" can be obtained for $0.25 sent to *Chemical Abstracts*, The Ohio State University, Columbus 10, Ohio.
6. For *unit values, conversion factors, and equivalents*, see the following:
   (*a*) Units of Weight and Measure, Definitions and Tables of Equivalents, U.S. Department of Commerce, *Miscellaneous Publication* M121 (send $0.35 to the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C.).
   (*b*) Handbooks of which the following are of special interest to chemists:
   Chemical Engineers' Handbook (Perry), McGraw-Hill Book Company, Inc., N.Y., 1950.
   Handbook of Chemistry and Physics, Chemical Rubber Publishing Company, Cleveland, Ohio, 1947.
   Handbook of Chemistry (Lange), Handbook Publishers, Inc., Sandusky, Ohio, 1952.
7. For the symbols, signs, and abbreviations recommended for *British scientific publications*, see:
   (*a*) *J. Chem. Soc.*, **1951**, Pt. II, 1677–92.
   (*b*) Letter Symbols, Signs, and Abbreviations, British Standard 1991, British Standards Institution, 2 Park Street, London, W. 2.
8. For standard symbols for *chemical engineering*, see the first report of a committee of the American Institute of Chemical Engineers published in *Ind. Eng. Chem.*, **39**, 438–9 (1947). This is the same as Z10.2-1946 listed under 1 above. A revised list is scheduled for publication in 1955 in *Industrial and Engineering Chemistry* and in *Chemical Engineering Progress*.
9. For the latest list of recommended "Symbols for Physical and Chemical Quantities" issued by the International Union of Pure and Applied Chemistry, see this organization's *Comptes rendus de la Quinzième Conférence*, Amsterdam, September 1949 (write R. Delaby, 4 Avenue de l'Observatoire, Paris 6e).
10. There is a section on "Chemistry," with *definitions*, in the Appendix on Arbitrary Signs and Symbols in *Webster's New International Dictionary*, G. & C. Merriam Company, Springfield, Massachusetts.
11. Some of the *abbreviations* and *symbols* used in this Encyclopedia are listed in the front matter of each volume.

E. J. CRANE

UNLOADING DEVICES. See *Conveying*, Vol. 4, p. 374.

URACIL, NH.CO.NH.CO.CH:CH. See *Nucleic acids*, Vol. 9, p. 509.

URANINITE. See *Uranium and uranium compounds.*

URANIUM AND URANIUM COMPOUNDS

Uranium, U, atomic number 92, atomic weight 238.07 (238.03 from mass spectrographic and nuclear disintegration data), is a member of the actinide series of transition elements. The element was discovered in 1789 by Martin Heinrich Klaproth in a specimen of pitchblende from Saxony. The unusual new "half-metallic substance" was named uranium in honor of the discovery of the planet Uranus in 1781. In 1841, Peligot showed that Klaproth's substance was actually the oxide UO_2, and succeeded in producing the metal itself by reduction of uranium tetrachloride with potassium. In 1896, H. Becquerel first discovered the phenomenon of radioactivity in uranium, and thereby aroused a new interest in this previously obscure element, which has continued to the present.

Before the discovery that the rare naturally occurring uranium isotope U^{235} would undergo nuclear fission with slow neutrons, liberating vast amounts of energy, uranium had very limited uses; its most important role was as a source of radium, although small amounts had been employed in ceramics to produce colored glazes, and in catalysts for ammonia production. The use of uranium in connection with atomic energy has increased its value to so great an extent as to eliminate its use for any purpose other than for the release of nuclear energy.

Uranium occupies a central position in the release of nuclear energy either by fission or even by thermonuclear reactions. All schemes suggested for the release of nuclear energy up to the present (1955) involve uranium, in one way or another, and the chemistry and technology of this element thus are of paramount importance. See *Nucleonics*.

A large number of both natural and synthetic isotopes of uranium are known (see Table I). The element uranium as found in nature consists of the three isotopes of mass numbers 238, 235, and 234 with relative abundances of 99.28, 0.71, and 0.006%,

TABLE I. Isotopes of Uranium.

Isotope	Half-life	Mode of decay
U^{227}	1.3 min.	α
U^{228}	9.3 min.	α
U^{229}	58 min.	α; electron capture
U^{230}	20.8 days	α
U^{231}	4.2 days	electron capture
U^{232}	70 yr.	α
U^{233}	1.62×10^5 yr.	α
U^{234}(UII)	2.48×10^5 yr.	α
U^{235}(AcU)	7.13×10^8 yr.	α, γ
U^{236}	2.46×10^7 yr.	α
U^{237}	6.75 days	β^-
U^{238}(UI)	4.50×10^9 yr.	α
U^{239}	23.5 min.	β^-
U^{240}	14.1 hr.	β^-

respectively. The isotope U^{238} is the parent of the natural uranium $4n + 2$ radioactive series, and the isotope U^{235} is the parent of the natural actinium $4n + 3$ radioactive series. Thus U^{238} and U^{234} are linked by radioactive decay, whereas U^{235} is of other origin. The isotopes U^{233} (synthetic) and U^{235} (natural) undergo fission with slow neutrons. The importance of these isotopes can be judged by the fact that complete fission of U^{235} gives rise to an amount of "heat energy equivalent" of about 10,000,000 kilowatt hours per pound. See also *Radioactive elements, natural.*

Since uranium is the longest known and most intensively studied of the actinide elements, and exhibits very complex chemical behavior, it is necessary to confine attention in this article to those aspects of the chemistry of uranium most pertinent to its technology. For complete references to work prior to 1936, see reference (15). Croxton (3) has compiled a valuable survey which abstracts all nonsecret publications on uranium chemistry prior to 1951. For a critical compilation of much of the older literature, together with a description of recent work, see reference (19).

Occurrence

Distribution. Uranium is widely distributed in nature. Table II lists estimates of the concentration of uranium present in various occurrences. There is a relationship between the silica content of igneous rocks and the uranium content; in general high-silica (acid) rocks such as granite contain the higher concentrations of uranium, while basic rocks such as the basalt that forms the floors of the oceans usually are found to contain much smaller amounts of uranium. Most sedimentary rocks, with the notable exception of the carnotite-bearing sandstones of the American Southwest and Soviet Kazakstan, carry negligible amounts of uranium. Marine shales and phosphate rock, which are also of sedimentary origin, also contain significant amounts of uranium. In sea water, uranium is present only to the extent of about one two-thousandths as much as is present in an equal weight of rock; nevertheless, even at this very low concentration all of the oceans are estimated to contain a total of 10^{10} tons of uranium. Despite the impression that uranium is an excessively rare element, it is present in the earth's crust to a much larger extent than such familiar elements as cadmium, bismuth, mercury, and silver. This merely illustrates that there is no simple relationship between the concentration of an element in the earth's crust and the probability of discovering economically important deposits of that element.

TABLE II. Uranium Occurrence in Nature.

Occurrence	Concentration, g. U/g.
Igneous rocks[a]	4×10^{-6}
Basalts	0.2×10^{-6}
Granites	25×10^{-6}
Sedimentary rocks[b]	2×10^{-6}
Meteorites[c]	10^{-9}
Ocean water[d]	2×10^{-9}
Living matter	10^{-4}–10^{-9}

[a] Mean concentration in the earth's crust.
[b] With the exception of the sedimentary rocks of the Colorado plateau which contain on the average a much higher concentration.
[c] This may be an upper value, and the true value may actually be much smaller.
[d] For sea water of 3.5% salinity.

Minerals. A very large number of uranium minerals have been characterized by mineralogists (14). Table III lists a number of the more common uranium minerals. Uranium minerals are very widely distributed; they are found in pegmatites, in veins arising from hydrothermal action, in disseminated deposits in igneous rocks, in sedimentary deposits, and in deposits associated with carbonaceous matter. The pegmatitic minerals, one of the most important being uraninite, are very widely distributed geographically. *Uraninite* as originally deposited is an oxide of uranium which, in the absence of severe weathering probably approximates the composition UO_2, but usually contains Pb and U^{6+} formed during radioactive decay; weathering also causes the formation of U^{6+}. Other primary uranium minerals found in pegmatites are uranium-bearing rare earth niobates, tantalates, and titanates; these are by far the most numerous class of uranium minerals found in pegmatites. Although the number of minerals found in pegmatites is very large, these minerals are present, in general, in very minor amounts and have little or no economic significance.

TABLE III. Common Uranium Minerals.

Name	Chemical composition	Uranium, %	Color	Luster	Sp.gr.	Hardness
Uraninite	Ideally UO_2 (also contains Pb, Th, rare earths)	45–85	Black, gray	Glossy, dull, submetallic	8–10.6	5–6
Pitchblende (a variety of Uraninite)	$UO_{2.2}$–$UO_{2.67}$	Variable	Black	Pitchlike, dull	6–8	5–6
Thucholite	Uranium oxide and hydrocarbons	Variable	Black	Dull, pitchy	2	3–4
Fergusonite	$(Y,Er,Ce,Th,Fe)(Nb,Ta,Ti)O_4$	0.2–8	Brown	Glossy	4–6	5–6
Euxenite-polycrase	$(Y,U,Ca,Th,Fe)(Nb,Ta)_2O_6$	3–12	Dark brown	Glossy	4–6	5–7
Samarskite	$(Y,U,Ca,Th,Fe)(Nb,Ta)_2O_6$	8.4–16.1	Black, brownish	Glossy	4–6	5–6
Pyrochlore-microlite	$(Na,CaU)_2(Ta,Nb)_2O_6(O,OH,F)$	2–15	Colorless, yellow, red, green, black	Glossy or resinous	4–6	5–6
Autunite	Hydrated $Ca(UO_2)(PO_4)_2.nH_2O$, n = 8–12	45–56	Lemon-yellow to apple green	Pearly, subadamantine	3.05–3.19	2–3
Carnotite	$K_2(UO_2)_2(VO_4)_2.nH_2O$, n = 1–3	~55	Yellow	Earthy	4	2–3
Tyuyamunite	$Ca(UO_2)(VO_4)_2.nH_2O$, n = 4–10	48–54	Yellow	Earthy	3–4	2–3
Uranophane	$Ca(UO_2)_2Si_2O_7.6H_2O$	57	Yellow, pale green, and pale orange	Pearly, greasy	3.81–3.90	2–3
Torbernite	$Cu(UO_2)(PO_4)_2.8$–$12H_2O$	47–51	Green	Pearly, subadamantine	3.2–3.6	2–2.5

Pitchblende, a variety of uraninite, the most important ore of uranium, is found in veins where it presumably has been deposited from hydrothermal solutions. The formula U_3O_8 is usually assigned to the mineral, but pitchblende is of a variable com-

position and only rarely does a sample correspond to this formula. Pitchblende is often metamict, as shown by diffuseness in the x-ray pattern, and differs from uraninites in containing much smaller amounts of thorium and rare earths. Pitchblende is found associated with a wide variety of minerals, the most important being sulfides and arsenides of iron, copper, nickel, cobalt, lead, silver, and bismuth. The presence of sulfide minerals in close proximity to pitchblende is common, although no uranium sulfides have been found in nature. Because pitchblende is soluble in even slightly acidic ground waters, secondary redistribution of uranium occurs, and pitchblende veins are frequently accompanied, particularly near the surface, by oxidation and alteration products. In these oxidized and altered deposits, the uranium minerals are present largely as phosphates, sulfates, arsenates, carbonates, hydrous oxides, and silicates and are distinguished by their bright colors.

Carnotite is a hydrous potassium uranyl vanadate, and *tyuyamunite* is the analogous calcium uranyl vanadate; the water content of both minerals is highly variable. *Autunite*, a hydrated calcium uranyl phosphate, is probably the most common uranium mineral. It occurs in small amounts in the oxidized zone of most uranium deposits and is derived from the alteration of such minerals as uraninite, pitchblende, gummite, uranophane, and the uranium-bearing niobates. Another very common uranium mineral is the hydrated copper uranyl phosphate, *torbernite*. Like autunite, torbernite is to be found in the oxidized zone of most uranium minerals; because copper is a necessary constituent, torbernite is not as prevalent in pegmatites as in typical pitchblende deposits, which commonly contain chalcopyrite and other copper sulfides.

Economic Deposits. Before 1942, no mining operations were conducted solely for the sake of obtaining uranium; mining was principally carried out for the recovery of radium, and the production of uranium was merely incidental. The discovery of nuclear fission, however, completely changed this picture, and occurrences of uranium which were uneconomic for the recovery of radium became extremely important as a source of the fissionable isotope U^{235}. Now, occurrences in which uranium is present even in very small amounts are being exploited. Ordinary economic criteria are for the most part irrelevant when applied to uranium production.

The most important uranium deposits are the hydrothermal vein deposits of pitchblende found in the Belgian Congo and in Canada. The primary vein deposits in the Shinkolowbe mine in the Congo are by far the richest so far described. The veins here vary in width from a few inches to several feet, and are associated with cobalt and copper sulfides, as well as significant quantities of molybdenum and iron sulfides, gold, platinum, and palladium. Numerous alteration products are found in the vicinity, the oxidized zone extending several hundred feet in depth. The Canadian deposits at Great Bear Lake and on Lake Athabaska are of the same general nature, pitchblende being found deposited in veins and fissures of the country rock. As in the Belgian Congo, the Canadian deposits are the result of a very complex process of mineralization, and the uranium is accompanied by some 40 minerals, the most important being pyrite and chalcopyrite. These pitchblende vein deposits appear to be exceedingly rare. Related to these geologically are the vein deposits of Czechoslovakia and Saxony.

The sandstone-type deposits of the Colorado Plateau have become significant producers of uranium. Most of the ore deposits are irregular in shape; they are often associated with fossilized tree trunks, branches or leaves. The principal ore minerals are carnotite and tyuyamunite, and, in the less oxidized ores, pitchblende and coffinite.

All of these are associated with corvusite, montroseite, hewettite, and other vanadium minerals. These are usually found as replacements of fossilized wood and as a coating on the grains of sandstone, and much of the ore contains 0.2–0.4% U_3O_8 and 1.5–2% V_2O_5.

While vanadiferous uranium ore remains the principal type mined, nonvanadiferous ores that contain pitchblende with copper sulfides and secondary minerals have assumed an increased significance. These ores are found in the western and southern parts of the Plateau, mostly in southern Utah and northern Arizona in the Moenkopi, Shinarump, or Chinle sandstone formations. These deposits, like carnotite, are spotty and erratic in distribution. Also occurring in southern Utah are uranium-bearing asphalts. Uranium-bearing asphaltic sandstone deposits containing an average of 0.2% U_3O_8 have been worked as economic producers of ore. While limestone formations containing commercial concentrations of uranium are relatively rare, nevertheless uranium-bearing limestone deposits having commercial significance (0.2% U_3O_8 and 0.15% V_2O_5) are found in the Zuni Uplift in northeastern New Mexico. The discovery of these sources of uranium on the Colorado Plateau have contributed significantly to the uranium derived from the region.

Materials containing less than 0.03% uranium can scarcely be described as ore. Nevertheless such occurrences are very widely distributed and occur in immense amounts, so that in the aggregate they represent enormous uranium reserves. For example, uranium in significant amounts has been reported in phosphate deposits in Russia, Morocco, Algeria, Tunisia, and Egypt, in the phosphoria formation in Idaho, Montana, and Wyoming, and in the Hawthorne and Bone Valley formations of central Florida. All marine phosphate formations contain uranium, generally, although not invariably, in proportion to the phosphate content. In Florida, only phosphate rock of marine origin ("land pebble" type) contains significant amounts of uranium. Concentration of the uranium is greatest in the upper or "leached" zone of the Bone Valley formation, and much less in the underlying "matrix" phosphate which is the principal source of commercial phosphate. Most of the uranium appears to be incorporated into the mineral carbonate-fluoroapatite, in which the uranium probably replaces part of the calcium. Small amounts of minerals in the torbernite and autunite group have been found in some of the phosphate deposits. Although it is uneconomical to process phosphate deposits containing 0.01–0.03% U_3O_8 solely for uranium, it is feasible to recover uranium economically as a by-product of phosphate fertilizer operation under special conditions. See *Phosphoric acids and phosphates.*

It has been known for many years that low concentrations of uranium are to be found in shales in many parts of the world. The first observation of uranium in black shales was in Sweden in an alum shale in 1893. Since that time uranium has been found in black shales in Russia, Estonia, Alaska, and the central continental United States. In the U.S., the Chattanooga formation is a radioactive black shale distributed over wide areas in Tennessee, Kentucky, and adjacent states, and formations correlative to the Chattanooga extend throughout Indiana, Kentucky, Ohio, and Michigan; these cover in the aggregate many thousands of square miles. Although the concentrations of uranium are low, say 0.008% U_3O_8 in the most radioactive Chattanooga shales of central Tennessee and southern Kentucky, the vast tonnages of shale which exist make the total amount of uranium present very large. No definite minerals have been identified in the Chattanooga shale. These shales represent a huge potential reserve of uranium, as do the lignite deposits of the Dakotas.

One other occurrence, in which uranium is present in very low concentration but where special circumstances make the recovery of by-product uranium feasible, is in the Rand gold fields of South Africa. Here the gold is accompanied by small amounts (0.01% U_3O_8) of uranium present in part as the mineral thucholite. Since enormous amounts of the gold ore are processed daily, appreciable amounts of uranium can be recovered from the residues of the gold extraction operations.

Extraction

Many of the details of the extractive metallurgy of uranium are carefully guarded trade secrets or are restricted for other reasons. In addition, uranium ores are often very complex chemically and vary a good deal in composition, necessitating changes in operating procedure. For these reasons it is difficult to give a very detailed description of the extraction of uranium. Nevertheless, certain gross features are present in all procedures: first, concentration of the ore; then a leaching operation which is often preceded by roasting; and finally recovery of the uranium from the pregnant leach liquors, usually by a precipitation process. The extractive metallurgy of uranium has been discussed by McDonald (23).

CONCENTRATION

The primary minerals, pitchblende and uraninite, have a high density and are readily concentrated by gravity if in large enough pieces. Thus, gravity concentration can be used at Shinkolowbe and the Eldorado Lake Athabaska deposits in Canada. However, most secondary uranium minerals such as autunite, torbernite, and gummite are soft and easily slimed, and gravity concentration fails to recover the uranium with sufficient efficiency. In earlier times, relatively high-grade ores were concentrated by hand picking. A device has been constructed which is actuated by the radioactivity of the ore and which appears to offer promise in the mechanical concentration of uranium ores. In the case of carnotite, which often occurs as a thin coating on the matrix silica, mechanical methods of concentrating the mineral values offer promise; by a gentle grinding and passage through a 200-mesh sieve (roughly the size of the individual quartz grains) much of the carnotite can be recovered (8). Flotation methods do not seem to have been widely applied. Although all the common uranium minerals can be readily floated, a very large number of other minerals, in particular calcite and quartz, can also be floated; and, since these are common gangue materials, flotation is not at present sufficiently selective. Bulk flotation, however, has been employed to achieve a low concentration ratio and to reject a reasonably large portion of the feed as a barren tailing.

ROASTING

Prior to the leaching operation, roasting is frequently resorted to. Thus, with Canadian Eldorado pitchblende ore, roasting with sodium chloride at 800°C. is carried out to convert native silver to insoluble silver chloride and to decompose carbonates, which cause frothing during subsequent acid leaching; sulfur, arsenic, and antimony are volatilized during the roasting. Roasting with sodium chloride at 850°C. is employed for carnotite ores when it is desired to recover vanadium; percolation of the calcines with water extracts the vanadium as water-soluble sodium vanadate, leaving the uranium values to be recovered by subsequent acid leaching. Many carnotite

ores are associated with appreciable amounts of carbonaceous matter that make grinding very difficult and that also interfere with subsequent acid treatment. Roasting destroys the organic matter and simultaneously converts any iron present to an acid-insoluble oxide. It is claimed that exceptionally high recovery of the mineral values from Plateau ores can be achieved by utilizing this roasting procedure (9).

LEACHING

In the case of uranium minerals, either an acid or an alkaline leach may be employed to convert the uranium to soluble compounds.

Acid Leaching. Pitchblende ore may be treated with dilute sulfuric acid, which can often be manufactured from pyrite occurring in the uranium ores. Since uranium as U^{4+} is sparingly soluble in the acid extract liquors, it is necessary to have an oxidizing agent present to convert all of the uranium to the +6 state as uranyl, UO_2^{2+}. Ferric iron is an excellent oxidizing agent for this purpose; it can sometimes be manufactured by aeration at pH 5–6 from the ferrous iron naturally present in the ore. Ferric ion performs a dual function in that it can also complex any phosphate present which might otherwise precipitate uranium. Manganese dioxide and sodium chlorate are also effective oxidants, and the choice of oxidizing agent depends upon cost and availability at a particular site. For satisfactory recovery of uranium by cold dilute acid leaching, it is advisable to use enough acid so that the pulp at the end of leaching has a pH of about 1.5. Optimum extractions are usually attained in 16–24 hours. Acid leaching can be carried out by countercurrent extraction, but it is more common to employ a single-step leach. Separation of the acid pregnant solution may be carried out by filtration or by countercurrent decantation; filtration requires the addition of organic flocculants such as glue, linseed meal, or sodium carboxymethyl cellulose in order to attain good filtration behavior.

Acid leaching of carnotite ores has been used in several mills on the Colorado Plateau. Hydrochloric acid has been used to some extent, being readily available by condensation from the flue gases produced during preliminary roasting of the ore with sodium chloride. After the soluble vanadium is extracted with water, the residue is leached with dilute hydrochloric acid. Carnotite ores can also be leached satisfactorily with sulfuric acid. One of the serious limitations of acid leaching is the nature of the gangue minerals; if these are siliceous, then little excess acid will be consumed; but if the gangue is largely calcium carbonate, acid consumption will be prohibitive, and an alkaline leach must then be used.

Numerous methods have been explored for the separation and recovery of uranium from other impurities in acid leach liquors. Many of these methods, as in the metallurgy of other elements, are related to gravimetric analytical procedures, and, in the case of uranium, are based on the insolubility in water of alkali metal uranates and diuranates, uranyl peroxide, phosphate, molybdate, vanadate, and arsenate. Ion exchange and solvent extraction methods have also been considered but details here are lacking.

Carbonate leaching can be carried out in simple equipment with good efficiency. Even though recovery of uranium is not quite as good as with acid, the absence of corrosion problems and the relatively inexpensive equipment makes carbonate leaching the preferred method in many cases. It is perhaps most widely used in the U.S. on the carnotite ores of the Colorado Plateau. Where the gangue is carbonate, as it often is on the Plateau, it is essentially the only method available.

Carbonate leaching depends for its efficacy on the fact that hexavalent uranium is soluble in excess carbonate as the tricarbonatouranyl ion, $[UO_2(CO_3)_3]^{4-}$. Forward, Halpern, and Peters (12) have made a detailed study of the carbonate leaching of ores, with special reference to Canadian pitchblende. In carbonate leaching, atmospheric oxygen can be utilized to complete the oxidation of uranium to the +6 state:

$$U_3O_8 + \tfrac{1}{2}\,O_2 + 9\,CO_3^{2-} + 3\,H_2O \longrightarrow 3\,UO_2(CO_3)_3^{4-} + 6\,OH^-$$

An equilibrium exists between the soluble tricarbonatouranyl ion and insoluble sodium uranate, which is a function of the hydroxide ion concentration:

$$UO_2(CO_3)_3^{4-} + 4\,OH^- + 2\,Na^+ \rightleftharpoons Na_2UO_4 + 3\,CO_3^{2-} + 2\,H_2O$$

Uranium can thus be precipitated from a carbonate solution by increasing the hydroxide ion concentration. In the actual leaching operation, it is therefore important to control the hydroxide ion concentration, since an accumulation of hydroxide will precipitate insoluble uranium salts and prevent effective leaching. This can be accomplished by addition of sodium bicarbonate or carbon dioxide. As described by Forward *et al.* (12) the optimum concentration of sodium carbonate is 50 grams/liter; leaching is carried out in a pressure vessel at 100°C. and 2 atm. oxygen pressure. Carbonate leaching requires much closer control than does acid leaching to attain maximum effectiveness.

In applying carbonate leaching to carnotite ores, roasting is resorted to only if the ore contains more than 1% vanadium; otherwise the raw ore is leached directly with the sodium carbonate. Roasting is commonly done with 6–9% sodium chloride at 850°C. for 1–2 hours. If the temperature exceeds this, insoluble uranium and vanadium compounds are formed; if lower, subsequent extraction is decreased. The presence of large amounts of calcium may cause difficulties by the formation of insoluble calcium vanadate. It is very important that after roasting the calcine be quenched immediately in sodium carbonate solution; if the calcine cools appreciably before quenching, the solubility of uranium is less than if the calcine is quenched at maximum heat. Low-vanadium ores, both of the high-lime and low-lime type, as well as asphaltic ores, are amenable to direct carbonate leaching without a salt roast. However, the settling characteristics of the ores are often greatly improved by a low-temperature roast at 300–500°C. The leaching solutions must be kept as hot as possible and excess carbonate or hydroxide must be avoided.

Two standard methods are available for the recovery of uranium from carbonate leach liquors. The carbonate solution may be acidified to pH 3 and boiled or evacuated to remove all carbon dioxide, after which the uranium can be precipitated by neutralizing to pH 7 with ammonia or sodium hydroxide. Alternatively, sodium hydroxide can be added directly to the carbonate solution to raise the pH above 11, whereupon reasonably complete precipitation of the uranium occurs. If the uranium and vanadium are present in the carbonate leach liquors in the proper stoichiometric ratio, then neutralization by acid leads to the very complete precipitation of sodium uranyl vanadate, the "yellow cake" of Colorado Plateau extractive metallurgy. Forward, Halpern, and Peters (12) have made a laboratory study of the recovery of uranium from carbonate solutions. They have shown that hydrogenation by gaseous hydrogen at 150°C. in the presence of a nickel catalyst will reduce the uranyl carbonate complex, and a black hydrated uranium dioxide will be precipitated. The barren solution is suitable for re-use. This sequence of operations presents the possibility

of extracting uranium in such a way that the only chemicals used up are oxygen (during the leach) and hydrogen (during uranium recovery).

Uranium Metal

PROPERTIES

Uranium is a very dense and highly reactive metal which possesses peculiar and unusual metallic properties. Because of its great importance in nuclear technology, it has been very intensively studied. Here only the most important of the properties of the metal can be described.

Constants. *Melting Point, Boiling Point, and Vapor Pressure.* Uranium metal for many years was considered to be a refractory metal like chromium, molybdenum, and tungsten. It melts, however, at a much lower temperature, which Dahl and Cleaves (5) have found to be 1130° ± 2°C. (2071°F.). The heat of fusion has been calculated to be 4.7 kg.-cal./gram-atom.

The boiling point of uranium has been estimated at about 4000°C. A precise measurement of the vapor pressure of liquid uranium (32) yields the following equation in the range 1630–1970°K.:

$$\log p_{\text{mm.}} = -\frac{(23330 \pm 21)}{T} + (8.583 \pm 0.011)$$

This expression leads to a value of 116.6 kg.-cal./gram-atom for the heat of sublimation of uranium at 0°K.

Phase Transitions and Crystal Structure. Three distinct solid phases of uranium exist. The room temperature or α form exists to about 665°C. Between 665 and 775°C., uranium exists in the β form, while the γ phase is the stable one between 775°C. and the melting point (1130°C.). These three phases have quite different crystal structures and mechanical properties and are responsible for a considerable portion of the complexities encountered in fabricating the metal.

Crystal structure studies on the various uranium phases are summarized in Table IV.

TABLE IV. Crystal Structure of the Various Uranium Phases.

Phase	Class	Lattice parameters, A.			No. of atoms per unit cell	Density, g./cu.cm.
		a_1	a_2	a_3		
α	Orthorhombic	2.858	5.877	4.955	4	19.00
β	Tetragonal	10.759	—	5.656	30	18.11 (at 720°C.)
γ	Body-centered cubic	3.524	—	—	2	18.06 (at 805°C.)

The α structure is a distorted hexagonal closest packing. It has been suggested that the uranium atoms are arranged in a layer structure of corrugated sheets, in which the binding within the sheets is stronger than that between the sheets, similar to the structures found in arsenic, antimony, and bismuth. The binding within the sheets shows a marked dependence on direction and thus can account for the anisotropy of α-uranium. The γ (high-temperature) modification of uranium can be stabilized at room temperature by the addition of small amounts of chromium or molybdenum. The β structure is very complex and has been the subject of much discussion. It is

related to the structure of α-uranium, but is of a very much lower order of symmetry and has a much larger unit cell.

Thermal Expansion. The coefficient of linear thermal expansion in α-uranium depends strongly on the crystallographic direction; this anisotropy makes the thermal expansion of uranium vary over a wide range (see Table V).

TABLE V. Coefficients of Linear Thermal Expansion of α-Uranium.

Direction parallel to the axis	Average expansion coefficient ($\times 10^6$), per °C.		
	25–125°C.	25–325°C.	25–650°C.
a (100)	21.7	26.5	36.7
b (010)	−1.5	−2.4	−9.3
c (001)	23.2	23.9	34.2
Volume coefficient ($\times 10^6$), per °C.	45.8	48.6	61.5

Mechanical Constants. Uranium is a relatively weak metal, only moderately ductile at room temperature, and its strength declines rapidly at elevated temperatures. The low-temperature α form has so low an elasticity that it has been described as "semiplastic."

Hardness of uranium is markedly affected by impurities; the hardness of cast uranium varies between 200 and 220 Brinell. Cold working increases the hardness and values ranging from 185 to 385 Brinell have been reported for uranium metal. The hardness falls rapidly above 200°C.; γ-uranium is so soft as to mitigate its use for fabrication, while the β phase is harder than the α, and considerably more brittle.

The yield strength of α-uranium is indeterminate since it is semiplastic. The variation in yield strength is great; most of the values lie in the range 25×10^3 p.s.i. (for 0.2% offset). Values of $15\text{–}30 \times 10^6$ p.s.i. have been given for Young's modulus; Poisson's ratio ranges between 0.23 and 0.42 p.s.i. and is in accordance with the semiplastic nature of uranium metal. The elasticity of uranium, like the hardness, decreases rapidly with increasing temperature in the α phase, but increases again in the β phase.

The ultimate tensile strength of uranium varies between 50,000 and 200,000 p.s.i. depending on the cold working and previous thermal history of the sample. Tensile strength falls rapidly at elevated temperatures, for example, from 53×10^3 p.s.i. at room temperature to 27×10^3 p.s.i. at 150°C. and 12×10^3 p.s.i. at 600°C.

Thermodynamic Properties of the Metal. Moore and Kelley (28) have given the following equations for the specific heat and heat content for the three uranium phases:

α-uranium: $C_p = 3.15 + 8.44 \times 10^{-3}T + 0.80 \times 10^{-5}T^{-2}$
β-uranium: $C_p = 10.38$
γ-uranium: $C_p = 9.10$
α-uranium (298–935°K.): $H_t - H_{298} = 3.15T + 4.22 \times 10^{-3}T^2 - 0.80 \times 10^5T^{-1} - 1046$
β-uranium (935–1045°K.): $H_t - H_{298} = 10.38T - 3525$
γ-uranium (1045–1300°K.): $H_t - H_{298} = 9.10 + 9.147T$

The entropy of α-uranium is $S_{298.16} = 12.03 \pm 0.03$ e.u.

Electrical and Thermal Conductivity. Uranium is a rather poor conductor, with an electrical conductivity about one-half that of iron. The highest conductivity so far reported is 4×10^{-4} (ohm-cm.)$^{-1}$. The highest conductivity and the greatest in-

crease in conductivity upon cooling to liquid nitrogen temperatures are indicative of superior purity. Pure uranium metal is superconducting below 1 °K.

The thermal conductivity of α-uranium increases from 28×10^{-3} cal./(sec.)-(sq.cm.)(°C./cm.) at 20 °K. to 64×10^{-3} at 300 °K.

REACTIONS

Uranium is a highly reactive metal. It reacts readily with all the nonmetallic elements and also forms numerous intermetallic compounds. The general chemical behavior of uranium in the electromotive series appears to be close to that of beryllium; it is thus strongly electropositive. Some of the chemical reactions which metallic uranium undergoes are listed in Table VI.

TABLE VI. Chemical Reactions of Uranium Metal.

Reactant	Reaction temperature, °C.[a]		Products
	Massive	Powdered	
H_2	250	−78	α- and β-UH_3
C	1800–2400	800–1200	UC; U_2C_3; UC_2
N_2	700	500	UN; $UN_{1.75}$; UN_2
P	—	600–1000	U_3P_4
O_2	150–350	Pyrophoric	UO_2; U_3O_8
S	500	—	US_2
F_2	25	—	UF_6
Cl_2	500–600	150–180	UCl_4; UCl_5; UCl_6
Br_2	650	210	UBr_4
I_2	350	260	UI_3; UI_4
H_2O	100	25	UO_2
HF(g)	—	200–400	UF_4
HCl(g)	—	250–300	UCl_3
NH_3	700	400	$UN_{1.75}$
H_2S	—	400–500	US; U_2S_3; US_2
NO	400–500	—	U_3O_8
CH_4	—	635–900	UC
CO	750	—	UO_2 + UC
CO_2	750	—	UO_2 + UC

[a] Temperature at which reaction begins.

Uranium metal exposed to air at room temperature soon assumes a golden yellow color which darkens gradually and which becomes black in three or four days. Cubicciotti (4) has investigated the oxidation of massive uranium metal and finds it to follow a parabolic law at low temperatures (90–165 °C.); the rate becomes linear at higher temperatures (165–215 °C.). Powdered uranium is frequently pyrophoric.

The reaction of uranium with water is complex. Boiling water attacks massive uranium slowly to form uranium dioxide and hydrogen. The rate of reaction increases as hydrogen accumulates because uranium hydride then forms. Steam reacts with uranium at 150–250 °C. to form a mixture of oxide and hydride:

$$7\ U + 6\ H_2O_{(g)} \xrightarrow{250°C.} 3\ UO_2 + 4\ UH_3$$

Although the exact composition of the oxide which forms is in doubt, all observers agree that the reaction of uranium with steam is more vigorous than with oxygen.

The reaction of uranium metal with aqueous hydrochloric acid is very rapid:

the U^{4+} ion is produced, but the reaction is evidently complex and its course depends on the normality of the acid used. Unless a large excess of acid is used, considerable amounts of a black solid, presumably hydrated uranium oxide, form. The addition of 0.05 *M* fluosilicic acid in concentrated hydrochloric acid completely dissolves uranium without the formation of black solids. Hydrobromic and hydriodic acids act similarly to hydrochloric acid but at a slower rate. Dilute sulfuric acid does not attack uranium metal appreciably, whereas hot concentrated sulfuric acid reacts slowly to form uranium(IV) sulfate. Phosphoric and hydrofluoric acids react only very slowly with uranium. Nitric acid dissolves uranium at a moderate rate; with finely divided uranium the reaction with nitric acid may assume explosive violence.

Uranium metal is inert to alkalies; however, the addition of oxidizing agents such as peroxide to caustic soda solutions leads to the dissolution of uranium metal with formation of soluble peruranates.

Since uranium is so reactive chemically, the melting and casting of uranium is one of the most difficult problems in uranium metallurgy. It is essential to protect metallic uranium, especially at elevated temperatures, from contact with air or moisture, and this has necessitated the development of special techniques in the fabrication and use of the metal.

PREPARATION

A variety of methods are available for the preparation of uranium metal. Since metallic uranium is a highly reactive substance, considerable attention has been directed to the production of massive rather than finely divided metal which is readily contaminated by exposure to air.

Reduction of Uranium Oxides with Carbon. This is the classic method employed by Moissan, who reduced U_3O_8 with sugar carbon at the temperature of the electric arc furnace. Metal so prepared invariably contains substantial amounts of carbon as uranium carbide.

Reduction of Uranium Oxides with Aluminum, Calcium, and Magnesium. The heat of formation of the uranium oxides is such that calculation shows them to be reducible by strong electropositive elements which form very stable oxides, such as aluminum, calcium, and magnesium. Such reactions can be carried out in an evacuated (or sealed) steel bomb tube. Thus Jander (17) produced metal of a fair degree of purity by reducing uranium dioxide with calcium at 950–1250°C. in a tightly sealed iron crucible. In general, this type of reaction, because of the high melting point of the slags which are formed (aluminum oxide, calcium oxide, and magnesium oxide), yields finely divided rather than aggregated or massive metal. Because the very finely divided metal is dispersed through the refractory slag, it is difficult to separate it in a pure condition. Calcium reduction of the oxide has been modified by carrying it out in the presence of alkali halides or alkaline earth halides which are reported to facilitate the reaction by acting as a flux and to yield metal in a coarser form (37,42,43). Magnesium metal has also been used to reduce uranium oxide, but since it tends to distill from the reaction mixture because of its high vapor pressure, it must be used in pressure vessels (39). Once started, the reaction is violent and difficult to control; it has been claimed that the use of a calcium-magnesium alloy of the approximate composition Ca_3Mg_4 is advantageous (43). Alexander (1) and Decroly and Van Impe (7) have used calcium hydride to reduce uranium oxide; the reaction is carried out in a Nichrome container at 960°C., the charge is allowed to cool in a vacuum to

eliminate hydrogen, and the metal is isolated by leaching away the calcium oxide with dilute acetic acid. The wet uranium powder is washed with water, dried, and processed by powder metallurgy (*q.v.*) techniques.

Aluminothermic methods for the reduction of uranium oxides have been studied by many workers (41). Since uranium and aluminum form alloys and intermetallic compounds, the use of aluminum as a reducing agent adds extra complications, even though it has been claimed that aluminum can be removed from uranium-aluminum alloys by vacuum fusion.

Reduction of Uranium Halides with Alkali Metals or Alkaline Earth Metals. The first preparation of uranium metal by Peligot in 1842 was by reduction of uranium tetrachloride with potassium. Since then the procedure has been employed frequently. It is clear that this procedure has marked advantages as compared to reduction with aluminum, calcium, and magnesium. The products of reduction of uranium halides such as the tetrachloride or the tetrafluoride, will, for example, be sodium fluoride, sodium chloride, or calcium chloride, or calcium fluoride. These melt at relatively low temperatures, far below the oxide slags produced by reduction of uranium oxide, which naturally facilitates the production of massive metal. Marden (38,40,44) has described the reduction of uranium halides (UF_4, KUF_5) by calcium, magnesium, calcium-magnesium alloys, and aluminum. The reduction of uranium tetrafluoride or similar halide by magnesium or calcium has been disclosed by Newton (48). Van Impe (36) has given a detailed description of the preparation of massive uranium metal on the 20-kg. scale by the reduction of uranium tetrafluoride with calcium. The reaction is highly exothermic and the heat evolved is sufficient to melt the uranium metal and the calcium fluoride slag. The reactor consists of an outer welded mild steel vessel lined with calcium fluoride. The uranium tetrafluoride is mixed with a 15% excess over the stoichiometric amount of calcium and is placed in the reactor. Reaction is initiated either by a magnesium ribbon or by the heat of a torch. Massive metal of high purity and in 98.5% yield is obtained.

Electrolytic Reduction of Uranium Halides. The electrochemical reduction of uranium halides in fused salt baths has been carried out according to methods devised by Driggs and Lilliendahl (10,45,46,47), Marden (24), and Meister (26). This process employs uranium tetrafluoride or the double salt KUF_5 dissolved in a fused electrolytic bath composed of 80% calcium chloride and 20% sodium chloride. A graphite container acted as the anode; the cathode was a molybdenum strip. The bath was operated at 900°C. and at a current density of 150 amp./sq. dm. The uranium deposit was granular and required washing and drying. Metal of better than 99.9% purity was obtained.

Thermal Decomposition of Uranium Halides. It has been found possible to prepare pure uranium metal by the "hot-wire" technique introduced by Van Arkel and De Boer for the preparation of very pure zirconium, titanium, and tungsten. In this process, uranium iodide is caused to undergo thermal decomposition to the elements on a hot filament. Since uranium has a much lower melting point than the refractory metals that have usually been obtained by this procedure, it is necessary to operate the filament at a relatively low temperature below the melting point of uranium. To achieve good results, very precise control over the operating variables is required; these have been discussed by Prescott, Reynolds, and Holmes (30). Very pure metal can be obtained, and this procedure thus has value for special purposes where very pure metal is required.

Fabrication. Uranium metal can be fabricated reasonably well by conventional procedures (34): forging, rolling, swaging, extruding, or drawing into plates, rods, bars, tubes, wire, or foil. Fabrication can be carried out either hot or cold; cold working requires the rate of reduction to be low. Hot working requires the use of protective atmospheres to prevent reaction with air; it is carried out in the α region with frequent reheats Uranium can be joined by forging or welding by the Heliarc torch in an inert atmosphere. Uranium can be machined by most of the usual methods provided certain precautions are followed: a lubricant is essential to prevent "burning," and a heavy cut at high speed should be made.

ALLOYS

Uranium forms alloys and intermetallic compounds with most of the metals; only a few examples can be cited. Thus, uranium forms compounds of the type U_6Fe, U_6Co, and U_6Ni with the transition elements; these are exceedingly brittle substances. Some of the intermetallic compounds of uranium with lead, bismuth, and tin are reactive, often being pyrophoric. A large number of alloy systems of uranium have been investigated among which are the uranium-aluminum, uranium-tungsten, uranium-molybdenum, uranium-zirconium, and uranium-thorium systems (27).

Uranium Compounds

At least four well defined oxidation states of uranium have been characterized (+3, +4, +5, +6), as well as numerous compounds which are semimetallic in nature. In this discussion, attention is focused on the technologically important solid compounds of uranium and on those aspects of its solution chemistry which have technological significance. Some other compounds are noted in Table VI.

Uranium Ions in Solution. Four oxidation states of uranium are known in aqueous solution: the +3, +4, and +6 states are stable, and the +5 state is relatively unstable, although millimolar solutions can be prepared and preserved at pH 2–4 for extended periods of time without disproportionation. The various oxidation states are all linked to each other by oxidation-reduction equilibriums, and each of the ions undergoes various kinds of hydrolytic behavior and complex ion formation in solution, all of which serve to complicate the chemistry of uranium in solution. In Table VII are summarized the thermochemical data on the ions in solution.

TABLE VII. Uranium Ions in Aqueous Solution.

Oxidation state	Ion in solution	Color	Thermochemical data		
			ΔH^0, kg.-cal./mole	ΔF^0, kg.-cal./mole	S^0, cal./(mole)(°C.)
+3	U^{3+}	Red	−123.0	−124.4	−30
+4	U^{4+}	Green	−146.7	−138.4	−78
(+5)	(UO_2^+)	—	−247.4	−237.6	12
+6	UO_2^{2+}	Yellow	−250.4	−236.4	−17

Oxidation-Reduction Behavior. Solutions of U^{3+} are readily prepared by dissolution of a trivalent uranium halide such as uranium trichloride, or by the electrolytic reduction of a solution of U^{4+} or U^{6+}. Aqueous solutions of U^{3+} are intensely red in color, unstable, and undergo oxidation to the +4 state readily by reduction of water. Strongly acidified solutions appear to be somewhat more stable.

Solutions of U^{4+} have a characteristic green appearance; they are much more stable than U^{3+} solutions but can still be oxidized easily to the +6 state even by mild oxidants such as molecular oxygen. U^{4+} in solution is converted to the +6 state by most of the common oxidizing agents. It has been shown that the U^{3+}/U^{4+} oxidation-reduction couple is reversible, but the U^{4+}/UO_2^{2+} couple is not.

The uranium +6 state is the most stable oxidation state of uranium in solution, the uranium being present primarily as the *uranyl ion*, UO_2^{2+}. Although the existence of this ion has on occasion been questioned, the evidence for its existence is overwhelming. Acidified UO_2^{2+} solutions are readily reduced by zinc, aluminum, magnesium, cadmium, silver, or copper, and by moderately strong reducing agents such as tin(II) chloride, titanium(III) chloride, or sodium hydrosulfite, $Na_2S_2O_4$, or electrolytically. In many cases, the uranium is reduced to a mixture of U^{3+} and U^{4+}; the U^{3+} can be removed by a short treatment with air.

The alternations in oxidation state which uranium shows in solution have great practical significance. This circumstance arises from the fact that uranium in different oxidation states gives rise to salts of greatly differing solubilities, and to complex ions of greatly different extractabilities. Consequently separations can be effected which might otherwise be very difficult. The oxidation-reduction potentials in acid solution are given in Table VIII.

TABLE VIII. Oxidation-Reduction Potentials of Uranium Ions.

Couple	Potential, volts
$U - U^{3+}$	1.80
$U^{3+} - U^{4+}$	0.61
$U^{4+} - UO_2^+$	−0.62
$UO_2^+ - UO_2^{2+}$	−0.05
$U^{4+} - UO_2^{2+}$	−0.334

Hydrolytic Behavior. Aqueous solutions of uranium salts always have an acid reaction indicative of hydrolysis. On the basis of pH measurements, the order of increasing hydrolysis is $U^{4+} > U^{3+} > UO_2^{2+}$; the degree of hydrolysis increases with increasing charge and decreasing ion size. In the case of U^{4+}, evidence indicates that the simple unoxygenated ion U^{4+} does exist in solution and that it is accompanied by hydrolysis products according to the equilibrium:

$$U^{4+} + 2\,H_2O \rightleftharpoons U(OH)^{3+} + H_3O^+$$

As the hydrolysis continues, polymeric species containing more than one atom of uranium bound together by oxygen or hydroxide bridges may appear. The hydrolysis of uranyl solutions has been intensively investigated and it has been concluded that the hydrolysis of UO_2^{2+} leads to the formation of the ions $U_2O_5^{2+}$ and $U_3O_8^{2+}$ rather than the monomeric species $UO_2(OH)^+$ and $UO_2(OH)_2$:

$$2\,UO_2^{2+} + H_2O \longrightarrow U_2O_5^{2+} + 2\,H^+ \qquad K = 1.1 \times 10^{-6}$$

$$U_2O_5^{2+} + UO_2^{2+} + H_2O \longrightarrow U_3O_8^{2+} + 2\,H^+ \qquad K = 5 \times 10^{-9}$$

$$U_3O_8^{2+} + H_2O \longrightarrow U_3O_8.OH^+ + H^+ \qquad K = 2.8 \times 10^{-4}$$

One of the practical consequences of this phenomenon is that solutions of uranyl chloride (or other uranyl salts) can dissolve very appreciable amounts of uranium trioxide to form polymeric ions.

Complex Ion Formation. It has been abundantly demonstrated that U^{4+} and UO_2^{2+} form numerous complex ions in solution with a large number of anions. Thus, variation of the oxidation-reduction potential of U^{4+} in solutions containing various anions shows that complex ions of the type UCl^{3+} exist, and that U^{4+} is complexed by sulfate, oxalate, and acetate ions. The situation with respect to UO_2^{2+} has received the greatest amount of attention and it has been shown, although details of some cases may be in doubt, that UO_2^{2+} is complexed among others by nitrate, sulfate, acetate, phosphate, bicarbonate, carbonate, pyruvate, lactate, citrate, maleate, thiocyanate, and salicylate ions. A simple rule which qualitatively indicates the strength of the complex is that the weaker the acid the stronger will be the complex which the anion of the acid forms; thus acetate or carbonate will form much stronger complexes with UO_2^{2+} than chloride or nitrate, since acetic and carbonic acids are much weaker than hydrochloric or nitric acids.

Analysis. Numerous procedures are available for the determination of uranium depending on the size of the sample and the uranium concentration. Uranium may be determined gravimetrically by precipitation as ammonium diuranate, uranium tetrafluoride, uranyl peroxide ($UO_4.2H_2O$), uranium(IV) "cupferrate" (see Vol. **1**, p. 875), and uranyl 8-hydroxyquinolinate. Titration procedures are usually preferred for macro amounts; the methods most often used involve the reduction of uranium(VI) by zinc or cadmium amalgam, and titration of the uranium(IV) formed by potassium permanganate, potassium dichromate, ceric sulfate, ferric sulfate, or potassium bromate. Titrations of uranyl ion directly with strong reductants such as chromium(II) and titanium(III) are also possible. For small amounts of uranium, colorimetric procedures using spectrophotometers are particularly useful. The color developed by sodium hydroxide-sodium peroxide or ferrocyanide is commonly used, although there are a very large number of reagents that develop colors with uranium. These methods are suitable for microgram amounts. Very small amounts of uranium can be assayed by measurement of the fluorescence radiation emitted by uranium; this method has been widely used for trace amounts in minerals and in biological specimens. Spectrophotometric, polarographic, and counting methods have also found use. Indeed none of the analytical techniques that may be utilized has escaped attention. A comprehensive and practical guide to the analysis of uranium is given by Rodden (33).

Uranium Halides.

Uranium tetrachloride, UCl_4, formula weight 379.90, is a dark green solid, m.p. 590°C., b.p. 792°C.

Uranium tetrachloride is markedly volatile; at its melting point of 590°C., it has a vapor pressure of 19.5 ± 1 mm. Hg. The vapor pressure of liquid uranium tetrachloride in the temperature range 590–790°C. can be expressed by the equation:

$$\log p_{\text{mm.}} = -\frac{7205}{T} + 9.65$$

Uranium tetrachloride forms metallic dark green octahedral crystals which have tetragonal symmetry, and which have a calculated density of 4.98 g./cu.cm. Its vapor density has been measured and the results show no association in the gas phase. Its heat of formation has been calculated to be $\Delta H_{273} = -250.9 \pm 0.6$ kg.-cal./mole.

Uranium tetrachloride is exceedingly hygroscopic and must be handled in a dry

atmosphere. It dissolves in water and other polar solvents such as alcohol with the evolution of heat to form a green solution characteristic of the +4 uranium state, and is insoluble in nonpolar solvents such as hydrocarbons, chloroform, or ether. Oxidizing agents convert uranium tetrachloride to the uranyl state in water. At elevated temperatures anhydrous uranium tetrachloride reacts with oxygen to form first uranyl chloride, UO_2Cl_2, and then U_3O_8. Chlorine reacts with uranium tetrachloride to give the higher uranium chlorides UCl_5 and UCl_6.

Uranium tetrachloride is prepared by the vapor-phase reaction of strong halogenating reagents such as carbon tetrachloride, phosphorus pentachloride, thionyl chloride, phosgene, or sulfur monochloride with uranium dioxide:

$$UO_2 + CCl_4 \xrightarrow{475°C.} UCl_4 + CO_2$$

Small amounts of phosgene, carbon monoxide, and chlorine are also found in the exit gases. The liquid-phase reaction of carbon tetrachloride with uranium trioxide can also be employed; this reaction proceeds rapidly at 250°C. under pressure. The primary product appears to be uranium hexachloride, which then undergoes dechlorination to uranium tetrachloride. Perhaps a more convenient liquid-phase reagent is hexachloropropene, $Cl_2C{=}CCl{-}CCl_3$, b.p. 210°C.; refluxing uranium trioxide with hexachloropropene at the boiling point under atmospheric pressure is a convenient preparation procedure. Although aqueous solutions of uranium tetrachloride can readily be prepared by electrochemical reduction of uranyl chloride solution, or by chemical reductants such as zinc amalgam, such procedures are not suitable if the anhydrous salt is required, since hydrated uranium tetrachloride cannot be dehydrated without extensive hydrolysis and oxidation. Purification of uranium tetrachloride can easily be accomplished either by sublimation or by fractional distillation in a vacuum.

Uranium tetrafluoride, UF_4, formula weight 314.07, is a green solid (the "green salt" of commerce), m.p. 1036°C., sp.gr. 6.70. This is one of the important uranium chemicals in nuclear technology, serving as the raw material for uranium hexafluoride preparation.

Uranium tetrafluoride is essentially nonvolatile, although it has been sublimed at 1000°C. in a very high vacuum. As obtained by sublimation, it consists of green needlelike crystals which possess monoclinic symmetry and which are isomorphous with ThF_4, CeF_4, and ZrF_4. The heat of formation of $UF_{4(cryst)}$ has been given as $\Delta H_{298} = -446$ kg.-cal. per mole and the free energy $\Delta F_{298} = -424.6$ kg.-cal. per mole.

Uranium tetrafluoride is insoluble in water and is not appreciably hygroscopic. With steam, the reverse of the hydrofluorination reaction occurs and at 800°C. uranium tetrafluoride is converted to uranium dioxide and hydrogen fluoride by steam. Oxidizing agents dissolve the tetrafluoride readily; perchloric acid, Ce^{4+} ion, and ammonia–hydrogen peroxide mixtures dissolve it without difficulty. Reagents which complex fluoride ion, such as Fe^{3+} or boric acid, are also effective for the dissolution of uranium tetrafluoride.

Uranium tetrafluoride can be prepared by the high-temperature hydrofluorination of uranium dioxide:

$$UO_2 + 4\,HF \xrightarrow{550°C.} UF_4 + 2\,H_2O$$

Hydrofluorination is a relatively slow reaction and its rate does not show much temperature dependence above 350°C. The use of a large excess of hydrogen fluoride has

been recommended. Other fluorinating agents can be used; thus the use of Freon 114 ($CClF_2CClF_2$) with uranium trioxide at 650–700°C. results in a good conversion to uranium tetrafluoride with a high bulk density (50). Van Impe (36) has described a process for the preparation of the tetrafluoride on a large scale; in this process, uranyl peroxide, $UO_4.2H_2O$, is converted to uranium trioxide by thermal decomposition at 250°C. The trioxide is then reduced with hydrogen to uranium dioxide at 600°C.; the dioxide is fluorinated using ammonium hydrogen fluoride, NH_4HF_2. The reactants are mixed and the reaction is carried out at 150°C. for 8 hours. The product of the reaction is a double salt, NH_4UF_5, and this is decomposed to uranium tetrafluoride by heating for 8 hours at 350°C., and for 4 more hours at 500°C.

It is also possible to produce the tetrafluoride in the "wet way." An aqueous solution of uranyl fluoride (or sulfate) is reduced with tin (II) chloride or electrolytically. Hydrated uranium tetrafluoride precipitates, after the addition of hydrofluoric acid where necessary; drying at 110°C. yields the monohydrate, $UF_4.H_2O$. Dehydration of this without concomitant hydrolysis and oxidation is difficult, but satisfactory dehydration can be achieved by drying the hydrate at 450°C. in an atmosphere of hydrogen fluoride.

Uranium hexafluoride, UF_6, formula weight 352.07, is a colorless compound which sublimes at atmospheric pressure at 56.54°C., and has a triple point at 64.02°C. at a pressure of 1134 mm. Hg. Uranium hexafluoride thus does not have a liquid phase except at pressures above atmospheric. Among uranium compounds of importance in nuclear technology, uranium hexafluoride is in the first rank. Being by far the most volatile compound of uranium it has found extensive use in the separation of uranium isotopes by thermal diffusion. Since all schemes for the release of nuclear energy involve at one point or another the only naturally occurring fissile isotope U^{235}, it is easy to appreciate the significance of the isotope separation process and the crucial role played in it by uranium hexafluoride.

Constants. A great number of studies on the physical constants of uranium hexafluoride ("Hex") have been made; some of these are summarized in Table IX (19,22). Its vapor pressure has been redetermined (29) and the results are given by the equations:

$$\log p_{\text{mm.}} = 6.38363 + 0.0075377t - 942.76/(t + 183.416) \quad (0\text{–}64°\text{C.})$$

$$\log p_{\text{mm.}} = 6.99464 - 1126.288/(t + 221.963) \quad (64\text{–}116°\text{C.})$$

$$\log p_{\text{mm.}} = 7.69069 - 1683.165/(t + 302.148) \quad (116\text{–}230°\text{C.})$$

These are probably the most accurate data on this important property at present available. A considerable volume of thermochemical data exists, and some of the most pertinent quantities are given in Table X. It is interesting to note that uranium hexafluoride gas closely approximates ideality at room temperature; Oliver, Milton, and Grissard (29) found that deviations of the gas from the ideal gas laws were very small, despite its high molecular weight. As a first approximation, many of the properties of uranium hexafluoride gas may be calculated from simple kinetic theory.

The structure of solid hexafluoride has been determined by x-ray methods. Uranium hexafluoride possesses orthorhombic symmetry with lattice parameters $a_1 = 9.900 \pm 0.002$, $a_2 = 8.962 \pm 0.002$, $a_3 = 5.207 \pm 0.002$ A. The unit cell contains four molecules and the calculated x-ray density is 5.060 ± 0.005 g./cu.cm. at 25°C. It has a typical molecular lattice, and the x-ray data indicate that the uranium hexa-

fluoride molecule in the solid is very close to octahedral symmetry. Burke, Smith, and Nielsen (2) have made a definitive study of the Raman and infrared spectra of uranium hexafluoride gas, and have shown quite conclusively that the molecule in the gas shows perfect octahedral symmetry.

TABLE IX. Some Physical Constants of Uranium Hexafluoride.

Property	Value[a]	Temp., °C.
Triple point, t_f, °C.	64.02 ± 0.05	—
Crit. temp., t_c, °C.	230.2 ± 0.2	—
Crit. pressure, P_c, atm.	45.5 ± 0.5	—
Ratio, c_p/c_v	1.063 ± 0.005	—
Density, solid, g./cu.cm.	5.09 ± 0.06	20.7
Density, liquid, g./cu.cm.	3.624	64.02
Self diffusion coeff., gas, sq.cm./sec.	0.081	30
Viscosity, liquid, centipoise	0.910	70
Viscosity, gas, micropoises	211	100
Sutherland's constant	101	—
Surface tension, dynes/cm.	16.8 ± 0.3	70
Parachor	200 ± 1	—
Refractive index, liquid, 4360 A.	1.383	70
Dielectric constant, gas	1.00297 ± 0.00006	59.5
Molar polarization, P, cu.cm.	27.0 ± 0.2	59.5
Thermal conductivity, gas, cal./(sec.)(sq.cm.)(°C./cm.)	1.42×10^{-5}	5

[a] Many of these values are selected for illustration from sets of data which give the value as a function of the temperature.

TABLE X. Thermochemical Data for Uranium Hexafluoride.

Property	Value
Heat of formation, ΔH_{298}	−505 ± 3 kg.-cal./mole
Free energy of formation, ΔF_{298}	−485 kg.-cal./mole
Heat of soln.: $UF_6(g) + 2\ H_2O(l) \rightarrow UO_2^{2+} + 2\ F^- + 4\ HF(aq)$	−50.5 ± 1.7 kg.-cal./mole
Heat of vaporization, ΔH_v	6.82 kg.-cal./mole (at 64.02°C.)
Heat of sublimation, $\Delta H_{sub.}$	12.02 kg.-cal./mole (at 0°C.)
Entropy, solid, S_{273}	51.05 cal./(mole)(°C.)
Entropy, liquid, S_{337}	73.17 cal./(mole)(°C.)
Entropy, gas, S_{273}	87.65 cal./(mole)(°C.)

Reactions. Uranium hexafluoride is a highly reactive substance, acting as a moderately powerful fluorinating agent. It reacts vigorously with water, forming *uranyl fluoride*, UO_2F_2, and hydrogen fluoride. Uranium hexafluoride does not react under ordinary conditions with oxygen, nitrogen, dry air, or carbon dioxide, although caution must be exercised with carbon dioxide since fluorination to carbonyl fluoride is potentially possible. Although uranium hexafluoride is soluble to a considerable extent in liquid chlorine or bromine, no reaction appears to occur with either gaseous chlorine or bromine, either in the cold or on heating. The reduction of uranium hexafluoride by hydrogen seems to have an unusually high energy of activation; Dawson and co-workers (6) report an initial rapid reduction at 250°C. which rather abruptly changes to a very slow process. At 330°C., the reaction is more than 50% complete in 30 minutes. Hydrogen chloride, bromide, and iodine rapidly reduce the hexafluoride to the tetrafluoride at 250°C. (49), and ammonia reacts even at dry-ice temperature to

form NH_4UF_5. Toward most organic compounds, uranium hexafluoride acts as a fluorinating agent. Alcohol, ether, benzene, toluene, and paraffin hydrocarbons react vigorously at room temperature to give hydrogen fluoride, UO_2F_2, and carbonaceous material. Solutions of uranium hexafluoride in some chlorinated hydrocarbons, however, are stable for several days; *sym*-tetrachloroethane appears to form particularly stable solutions. The completely fluorinated hydrocarbons are completely inert to the hexafluoride. The fluorine-containing polymers polytetrafluoroethylene (Teflon) and polychlorotrifluoroethylene (fluorothene Kel-F, CF-3) are resistant to uranium hexafluoride and are very useful materials for its manipulation (see also Vol. **11**, pp. 687, 691).

Preparation. Uranium hexafluoride is commonly prepared by the direct fluorination of uranium tetrafluoride:

$$UF_4 + F_2 \longrightarrow UF_6$$

This reaction becomes rapid above 250°C. All uranium compounds are converted to uranium hexafluoride with elemental fluorine. The temperature conditions for complete fluorination of uranium oxide, for example, are more severe, however, and the consumption of expensive fluorine for the production of undesired by-products becomes excessive when materials other than uranium tetrafluoride are used as starting materials. Elemental fluorine or a strong fluorination agent such as cobalt(III) fluoride are required to produce uranium hexafluoride. Certain reactions are known, however, which yield the hexafluoride without the use of elemental fluorine. The most interesting of these is the treatment of the tetrafluoride with oxygen at elevated temperatures:

$$2\ UF_4 + O_2 \xrightarrow{800°C.} UF_6 + UO_2F_2$$

While the yields are low and recycling of the uranyl fluoride is required, nevertheless this procedure is of interest since no elemental fluorine is required at any stage.

Uranium hexafluoride is in the category of highly reactive compounds and consequently problems are encountered in its handling. In the laboratory, properly cleaned glass equipment can be used. On a large scale, metal equipment, usually made of copper, nickel, or aluminum, is preferred. These metals are commonly used with elemental fluorine since they are self-protecting by the formation of a tightly adherent layer of fluoride. Since uranium hexafluoride is very sensitive to traces of moisture, it is necessary that all equipment be very dry and that precautions be taken against the entry of water. A common impurity in uranium hexafluoride arising often from traces of moisture is hydrogen fluoride which must be removed if the hexafluoride is to be handled in glass; even in metal equipment small amounts of hydrogen fluoride may greatly increase corrosion. Uranium hexafluoride containing gross amounts of hydrogen fluoride when pumped on at −80°C. forms a constant evaporation mixture containing about 2 mole per cent hydrogen fluoride; if this mixture is then treated with potassium fluoride, the hydrogen fluoride is removed by the formation of KHF_2.

Uranium Nitrate.

The only known nitrate of uranium is uranyl nitrate.

Uranyl nitrate (uranium(VI) dioxydinitrate), $UO_2(NO_3)_2{\cdot}6H_2O$, formula weight 502.18, is perhaps the most important of the water-soluble compounds of uranium. It forms three well-characterized hydrates containing six, three, or two molecules of

water. The hexahydrate is obtained by crystallization from water or dilute nitric acid; it is the familiar yellow salt of commerce commonly designated as UNH. The uranyl nitrate–water system has been studied by Marshall, Gill, and Secoy (25). See Figure 1. The heat of formation of $UO_2(NO_3)_2.6H_2O$ is −764.3 kg.-cal./mole and the entropy S_{273} is 120.85 cal./(mole)(°C.). The crystal structure of the hexahydrate is orthorhombic, with lattice parameters $a_1 = 11.44$, $a_2 = 13.18$, $a_3 = 8.04$ A.; there are 4 molecules per unit cell and the calculated density is 2.74 g./cu.cm.

One of the properties of uranyl nitrate which makes it a compound of importance is its solubility in organic solvents. The ready solubility of uranyl nitrate hexahydrate in diethyl ether has been known for a hundred years, and the ability of water-immiscible organic solvents to extract uranium from aqueous nitrate solutions has been used

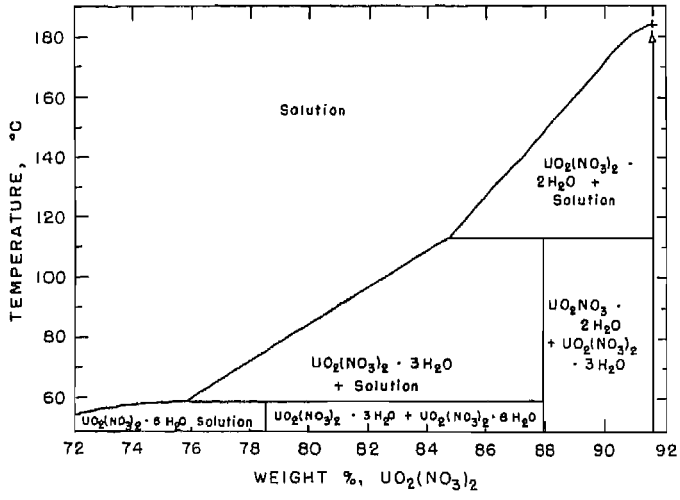


Fig. 1. The solubility of uranyl nitrate in water (25).

for purification of uranium. To facilitate extraction of uranium into nonaqueous solvents, it has been found convenient to use metal nitrates as salting agents; ammonium, calcium, aluminum, and ferric nitrates are typical of the salting agents. In the presence of such salting agents, it appears probable that the uranium is extracted as the trinitratouranyl ion, $[UO_2(NO_3)_3]^-$. Although diethyl ether has received much attention, solvents such as other ethers, ketones, alcohols, and others have also been studied; Katzin and Sullivan (20) give numerous phase diagrams of uranyl nitrate–water–organic solvent systems and may be consulted for details.

An engineering study of the extraction of uranyl nitrate by diethyl ether has been made by Jodra, Luina, and Oroz (18) using two types of extraction columns; one was a spray tower and the other a column packed with Raschig rings. Data for values of transfer coefficients, heat transfer unit, and heat-equivalent-to-a-theoretical-plate are given for both types of columns.

Uranium Oxides.

The uranium-oxygen system is one of the most complicated oxide systems in the periodic table. The law of definite proportions does not apply unambiguously to a system such as that of uranium and oxygen; the oxidation-reduction potential of

uranium is such that oxygen can be continuously added to or removed from a crystal of a given uranium oxide. Gain or loss of oxygen is compensated for by change in the oxidation state of the uranium atoms. In the uranium-oxygen system, it is possible to produce continuous infinitesimal changes in composition, and, rather than compounds with a definite stoichiometric composition, phases with a range of compositions exist. The situation is further complicated by the variation of the stable range of compositions for a given phase with temperature. Thus "UO_2" actually refers to a phase which has the same crystal structure and can vary in composition between $UO_{2.00}$ and about $UO_{2.30}$ without marked change in the crystal type. A detailed discussion of the uranium-oxygen system would thus require an analysis of these complicated phase relationships; for this, see references (16,19). In Table XI are summarized in a condensed and simplified form some pertinent facts about the phase relations in the uranium-oxygen system. However, much of the technological interest in the uranium oxides is centered in the oxides of "composition" UO_2, U_3O_8, UO_3, and UO_4.·

TABLE XI. Phase Relations in the Uranium-Oxygen System.

At 200°C.			At 1000°C.		
Composition	Phases	Crystal type	Composition	Phases	Crystal type
$UO_{2.00}$–$UO_{2.25}$	Monophasic	Fluorite (UO_2 type)	$UO_{2.00}$–$UO_{2.25}$	Diphasic	Fluorite + β-UO_2-($UO_{2.25}$)
$UO_{2.25}$–$UO_{2.3}$	Monophasic	Fluorite (β-UO_2) changing to tetragonal	$UO_{2.25}$–$UO_{2.50}$	Diphasic	β-UO_2 + orthorhombic
	Diphasic[a]	Fluorite + tetragonal			
$UO_{2.3}$–$UO_{2.6}$	Diphasic	Tetragonal + orthorhombic	$UO_{2.50}$–$UO_{2.62}$	Monophasic	Orthorhombic
				Diphasic	β-UO_2 + orthorhombic
$UO_{2.60}$–$UO_{3.00}$	Monophasic	Orthorhombic (U_3O_8 structure)	$UO_{2.62}$–$UO_{3.00}$	Thermally unstable	

[a] Number of phases depends on whether sample was heated above 200°C.; in heating above 200°, compositions in the range $UO_{2.25}$–$UO_{2.3}$ decompose into a mixture of UO_2 and $UO_{2.25}$ (β-UO_2).

TABLE XII. Physical Properties of Uranium Oxides.

Formula	UO_2	U_3O_8	UO_3	$UO_4.2H_2O$
M.p., °C.	3000 ± 200	1450 (dec.)	450 (dec.)	100 (dec.)
Thermochemical data				
ΔH^0, kg.-cal./mole	−259.2	−853.5	−291.6	−436
ΔF^0, kg.-cal./mole	−246.6	−804	−273.1	—
S^0, cal./(mole)(°C.)	18.63	66	23.6	—
Crystallographic data				
Cryst. form	Face-centered cubic	Orthorhombic	Hexagonal	Orthorhombic
Lattice parameters, A.				
a_1	5.468	6.721	3.971	8.74
a_2	—	3.988	—	6.50
a_3	—	4.149	4.168	4.21
No. of molecules per cell	4	2/3	1	2
X-ray density, g./cu.cm.	10.97	8.39	8.34	5.15

$2H_2O$, and attention here will be focused on these. For convenience a number of the important physical properties of the oxides are collected in Table XII.

The oxides of uranium, like other oxides, undergo a great variety of chemical reactions in addition to interconversions. Some of these are indicated in Table XIII.

TABLE XIII. Chemical Reactions of Uranium Oxides.

Reagent	Temp., °C.	Product		
		With UO_2	With U_3O_8	With UO_3
CO	350	No reaction	No reaction	UO_2
	750	No reaction	UO_2	UO_2
HF (g)	550	UF_4	$UO_2F_2 + UF_4$	UO_2F_2
CCl_4	400	UCl_4	$UCl_4 + UCl_5$	$UCl_4 + UCl_5$
Cl_2	900	UO_2Cl_2	UO_2Cl_2	—
S_2Cl_2	450	UCl_4	UCl_4	UCl_4
HBr	800	*No reaction*	UO_2Br_2	UO_2Br_2

The refractory nature of the uranium oxides has led to the preparation of uranium refractories that are useful in the handling of uranium at high temperatures. Details of the fabrication of such crucibles have been given by Eyerly, Lambertson, Kraft, and Corwin (11).

Uranium dioxide, UO_2, formula weight 270.07, is prepared by the reduction of UO_3 or U_3O_8:

$$UO_3 + H_2 \xrightarrow{700°C.} UO_2 + H_2O$$

$$UO_3 + CO \xrightarrow{350°C.} UO_2 + CO_2$$

$$U_3O_8 + 2\,CO \xrightarrow{750°C.} 3\,UO_2 + 2\,CO_2$$

The color of uranium dioxide varies from brown to black. Very finely divided uranium dioxide, prepared, for example, by the thermal decomposition of uranyl oxalate is frequently pyrophoric; the pyrophoric form is commonly black and the oxide of lower reactivity brown. Ignition at 700°C. in air forms U_3O_8.

Triuranium octoxide, U_3O_8, formula weight, 842.21, is that oxide of uranium which results from the ignition of any uranium oxide and indeed of almost all uranium compounds in air. At 700°C., the oxide obtained has a composition very close to $UO_{2.667}$ or U_3O_8. The oxide can be from olive-green to black-green or black in color. The higher the temperature of ignition the blacker the color, although even the blackest U_3O_8 samples give a green streak. Since U_3O_8 is the stable uranium oxide on ignition in air, it occupies an important place in uranium technology, with many uranium compounds being prepared from U_3O_8 and ultimately ending up as U_3O_8 again.

Uranium trioxide, UO_3, formula weight 286.07, can be obtained by the thermal decomposition of uranyl nitrate hexahydrate or ammonium diuranate; these two compounds are the usual final products from the ore extraction and purification procedure:

$$UO_2(NO_3)_2.6H_2O \xrightarrow{350°C.} UO_3 + N_2O_4 + 6\,H_2O + \tfrac{1}{2}\,O_2$$

$$(NH_4)_2U_2O_7 \xrightarrow{350°C.} 2\,UO_3 + H_2O + 2\,NH_3$$

Since uranium trioxide may undergo thermal decomposition at temperatures above 450°C., it is usually desirable to carry out its preparation at temperatures below 400°C.

in order to avoid formation of U_3O_8. It requires very careful control of the temperature to prepare a trioxide which on the one hand does not contain nitrogen because of incomplete ignition or, on the other hand, is free of U_3O_8. Uranium trioxide ranges in color from light yellow to orange to brick-red. It exists in an amorphous form and at least four crystalline modifications. The amorphous form may be prepared by the ignition of uranyl peroxide, $UO_4.2H_2O$, or uranyl oxalate at 380–400°C. Crystalline phases I, II, and III (arbitrary designations) are prepared by the oxidation of U_3O_8 with molecular oxygen at 450–750°C. at oxygen pressures of 30–150 atm. Phase III, the most stable thermally, results also from the decomposition of uranyl nitrate at temperatures below 400°C. Phase IV is the brick-red form resulting from the oxidation of U_3O_8 with nitrogen tetroxide or atomic oxygen at 250–350°C. Amorphous uranium trioxide begins to decompose at 400°C. in air; between 520 and 600°C. an oxide of composition $UO_{2.90}$ forms, and further heating at 600°C. results in the formation of U_3O_8. The decomposition of phase IV also begins at around 400°C., but if the solid is heated in air for several days, oxygen is reabsorbed and phase III, which is stable in air to 600°C., results.

Uranium Peroxide. Although anhydrous UO_4 does not exist, the dihydrate, $UO_4.2H_2O$, is readily prepared by addition of hydrogen peroxide to aqueous solutions of uranyl salts. This hydrate is one of the least soluble compounds of uranium known, and can be precipitated from quite acid solution. When it is dehydrated, it looses water and oxygen simultaneously until the lower oxides UO_3 or U_3O_8, depending upon temperature, result. Finely divided and reactive uranium trioxide can be made by the careful ignition of $UO_4.2H_2O$.

Mixed Oxides. Considerable attention has been devoted in recent years to mixed oxide systems. Lambertson and Mueller (21) have made a detailed study of the UO_2–Al_2O_3, UO_2–MgO, UO_2–ZrO_2, and UO_2–ThO_2 systems. The UO_2–Al_2O_3 systems show a simple eutectic at 1930°C. with no compounds or solid solutions. The UO_2–MgO system likewise shows a simple eutectic with no regions of solid solution or compound formation. The UO_2–ZrO_2 system, while it shows no new compounds, contains extensive regions of solid solution; cubic UO_2 can dissolve more than 50 mole per cent ZrO_2, while tetragonal ZrO_2 can dissolve 20 mole per cent of UO_2. The UO_2–ThO_2 system forms a continuous series of solid solutions over the entire composition range. Data on other ternary systems exist, particularly on UO_2 and U_3O_8 systems with lanthanide oxides (Pr_6O_{11}, Nd_2O_3, Er_2O_3); such systems have interesting electrical properties as do the uranium oxides themselves (13,31).

Uranates and Polyuranates.

An important class of compounds related to the uranium oxides is the metal uranates and polyuranates. The **alkali metal polyuranates** are obtained by the addition of alkali hydroxide to an aqueous solution of uranyl (UO_2^{2+}) salt. The precipitates so obtained are complex in composition. Two polyuranates are formed, $Na_2U_{16}O_{49}$ (yellow) and $Na_2U_2O_7$ (orange). When $Na_2U_{16}O_{49}$ is washed with water, it is converted to yellow $Na_2U_7O_{22}$. In the presence of excess alkali, the species which is stable is $Na_6U_7O_{24}$. The compound obtained by addition of ammonia to uranyl solutions is usually given the formula $(NH_4)_2U_2O_7$ but detailed investigation may discover complexities here also. Compounds of this class may also be prepared by fusion of U_3O_8 or UO_3 with a metal chloride (with the addition of metal chlorate to facilitate

oxidation of the uranium), or by ignition of metal uranyl double salts, for example, $Mg(UO_2)_2(C_2H_3O_2)_6.6H_2O$ or $BaUO_2(C_2O_4)_2$. By the use of the latter procedures, simple uranates of the formula Na_2UO_4 or $MgUO_4$ can be obtained.

The metal uranates and polyuranates are highly insoluble in water; uranium is frequently precipitated from aqueous solution as ammonium or sodium polyuranate because of the very low solubility of these compounds. These compounds are readily soluble, however, in acids. The uranates and polyuranates usually undergo a reversible loss of oxygen on heating to elevated temperatures. Ammonium diuranate, on the other hand, undergoes thermal decomposition to yield UO_3.

Uranium Sulfates.

Uranium(IV) sulfate, $U(SO_4)_2$, formula weight 430.21, forms a tetra- and octahydrate on precipitation from water. The octahydrate is precipitated from weaky-

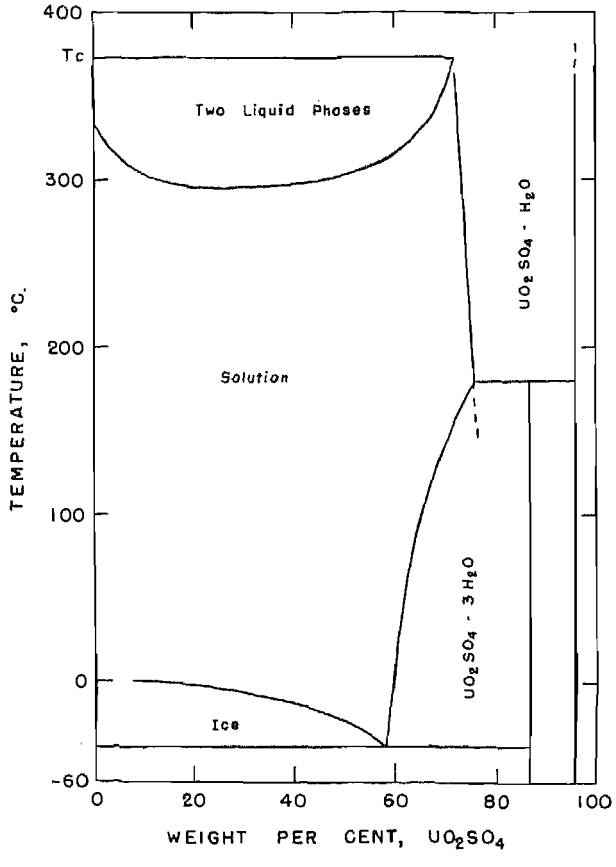


Fig. 2. Phase diagram for the system uranyl sulfate–water (35).

acid solution between 0 and 75°C., whereas the tetrahydrate is formed from strongly acid solution in this temperature range. The stability ranges of the various uranium(IV) sulfate hydrates have been given as:

$$U(SO_4)_2.8H_2O \xrightarrow{68°C.} U(SO_4)_2.4H_2O \xrightarrow{100°C.} U(SO_4)_2.2H_2O \xrightarrow{200°C.}$$

$$U(SO_4)_2.\tfrac{1}{2}H_2O \xrightarrow{300°C.} U(SO_4)_2$$

Uranium(IV) sulfate exhibits retrograde solubility and the material is more soluble in water at low temperatures than at higher ones. Uranium(IV) sulfate undergoes hydrolysis to form the sparingly soluble basic sulfate, $UOSO_4.2H_2O$.

Uranyl sulfate exists usually as the trihydrate, $UO_2SO_4.3H_2O$. The phase diagram of the uranyl sulfate–water system has been given by Secoy (35), and is shown in Figure 2.

Bibliography

(1) Alexander, P., *Metals and Alloys*, **8**, 265 (1937); **9**, 45 (1938).
(2) Burke, T. G., Smith, D. F., and Nielsen, A. H., *J. Chem. Phys.*, **20**, 447 (1952).
(3) Croxton, F. E., "Uranium and Its Compounds," *U.S.A.E.C. Rept.*, **K-295**, Pt. 2 (1951).
(4) Cubicciotti, D., *J. Am. Chem. Soc.*, **74**, 1079 (1952).
(5) Dahl, A. I., and Cleaves, H. E., *J. Research Natl. Bur. Standards*, **43**, 513 (1949).
(6) Dawson, J. K., Ingram, D. W., and Bircumshaw, L. L., *J. Chem. Soc.*, **1950**, 1421.
(7) Decroly, C., and Van Impe, J., *Bull. Assoc. Ing. U. L. B.*, **3**, 205 (1950).
(8) DeVaney, F. E., *Eng. Mining J.*, **139**, 43 (1938).
(9) Doerner, H. A., *U.S. Bur. Mines Rept. Invest.*, **2873** (1928).
(10) Driggs, F. N., and Lilliendahl, W. C., *Ind. Eng. Chem.*, **22**, 576 (1930).
(11) Eyerly, G. B., Lambertson, W. A., Kraft, R. G., and Corwin, R. E., *Argonne Natl. Lab. Rept.*, **5038** (March 1953).
(12) Forward, F. A., Halpern, J., and Peters, E., *Can. Mining Met. Bull.*, **46**, 634 (1953).
(13) Gruen, D. M., *J. Am. Chem. Soc.*, **76**, 2117 (1954).
(14) George, D., "Mineralogy of Uranium and Thorium," *U.S.A.E.C. Doc.*, **RMO-563** (Jan. 1949).
(14a) *Glossary of Uranium and Thorium-Bearing Minerals*, Catalog No. I 19.3: 1009-F, Government Printing Office, Washington, D.C., 1955.
(15) Gmelin, 8th ed., System-Nummer **55**, 1936.
(16) Hoekstra, H. R., and Katz, J. J., *Actinide Elements*, National Nuclear Energy Series, Div. IV, Vol. 14A, ch. 6, McGraw-Hill, N.Y., 1954.
(17) Jander, W., *Z. anorg. u. allgem. Chem.*, **138**, 321 (1924).
(18) Jodra, L. G., Luina, A. P., and Oroz, A., *Chem. Eng. Progress, Symposium Series*, **50**, No. 12, 127 (1954).
(19) Katz, J. J., and Rabinowitch, E., *The Chemistry of Uranium*, National Nuclear Energy Series, Div. VIII, Vol. 5, McGraw-Hill, N.Y., 1951.
(20) Katzin, L. I., and Sullivan, J. C., *J. Phys. Colloid Chem.*, **55**, 346 (1946).
(21) Lambertson, W. A., and Mueller, M. H., *J. Am. Ceram. Soc.*, **36**, 329, 365, 397 (1953).
(22) Llewellyn, D. R., *J. Chem. Soc.*, **1953**, 28.
(23) McDonald, R. D., *Chem. Eng. Progress, Symposium Series*, **50**, No. 11, 69 (1954).
(24) Marden, J. W., *Trans. Electrochem. Soc.*, **66**, 39 (1934).
(25) Marshall, W. L., Gill, J. S., and Secoy, C. H., *J. Am. Chem. Soc.*, **73**, 1867 (1951).
(26) Meister, G., *Metal Progress*, **53**, 515 (1948).
(27) Meister, G., in Hampel, *Rare Metals Handbook*, Reinhold, N.Y., 1954.
(28) Moore, G. E., and Kelley, K. K., *J. Am. Chem. Soc.*, **69**, 2105 (1947).
(29) Oliver, G. D., Milton, H. T., and Grissard, J. W., *J. Am. Chem. Soc.*, **75**, 2827 (1953).
(30) Prescott, C. H., Jr., Reynolds, F. L., and Holmes, J. A., *U.S.A.E.C. Rept.*, **MDDC-437** (1946).
(31) Prigent, J., *J. Phys. Radium*, **10**, 58 (1949).
(32) Rauh, E. G., and Thorn, R. J., *Argonne Natl. Lab. Rept.*, **ANL-5203** (Jan. 1954).
(33) Rodden, J. C. (ed.), *Analytical Chemistry of the Manhattan Project*, National Nuclear Energy Series, Div. VIII, Vol. 2, McGraw-Hill, N.Y., 1950.
(34) Saller, H. A., and Rough, F. A., *Chem. Eng. Progress, Symposium Series*, **50**, No. 11, 63 (1954).
(35) Secoy, C. H., *J. Am. Chem. Soc.*, **70**, 3450 (1948); **72**, 3343 (1950).
(36) Van Impe, J., *Chem. Eng. Progress*, **50**, 230 (1954).
(37) Brit. Pat. 238,663 (July 7, 1924), A. Cachemaille.
(38) U.S. Pat. 1,437,984 (Dec. 5, 1922), J. W. Marden (to Westinghouse Lamp Co.).

(39) U.S. Pat. 1,602,542 (Oct. 12, 1926), J. W. Marden (to Westinghouse Lamp Co.).
(40) U.S. Pat. 1,646,734 (Oct. 25, 1927), J. W. Marden (to Westinghouse Lamp Co.).
(41) U.S. Pat. 1,648,954 (Nov. 15, 1927), J. W. Marden (to Westinghouse Lamp Co.).
(42) U.S. Pat. 1,659,209 (Feb. 14, 1928), J. W. Marden (to Westinghouse Lamp Co.).
(43) U.S. Pat. 1,738,669 (Dec. 10, 1929), M. N. Rich (to Westinghouse Lamp Co.).
(44) U.S. Pat. 1,814,721 (July 14, 1931), J. W. Marden (to Westinghouse Lamp Co.).
(45) U.S. Pat. 1,821,176 (Sept. 1, 1931), F. H. Driggs and J. W. Marden (to Westinghouse Lamp Co.).
(46) U.S. Pat. 1,842,254 (Jan. 19, 1932), F. H. Driggs (to Westinghouse Lamp Co.).
(47) U.S. Pat. 1,861,625 (June 7, 1932), F. H. Driggs and W. C. Lilliendahl (to Westinghouse Lamp Co.).
(48) U.S. Pat. 2,446,780 (Aug. 10, 1948), A. S. Newton (to the U.S. Atomic Energy Commission).
(49) U.S. Pat. 2,638,406 (May 12, 1953), A. D. Tevebaugh and F. Vaslow (to U.S. Atomic Energy Commission).
(50) U.S. Pat. 2,674,518 (April 6, 1954), E. C. Evers and M. B. Reynolds (to U.S. Atomic Energy Commission).

J. J. KATZ

URANOPHANE, $Ca(UO_2)_2Si_2O_7.6H_2O$. See *Uranium and uranium compounds.*

URAZOLE, NH.NH.CO.NH.CO. See *Heterocyclic compounds*, Vol. **7**, p. 444.

UREA AND UREA DERIVATIVES

Urea (carbamide), NH_2CONH_2, may be considered to be the amide of carbamic acid, NH_2COOH, or the diamide of carbonic acid, $CO(OH)_2$. It is a white odorless crystalline solid with a cool saline taste resembling sodium nitrate. In mammals, it is formed during the decomposition of proteins (*q.v.*) as the chief final product of nitrogen metabolism and is excreted in the urine.

Urea has found many industrial uses, among the most important being: in agriculture as a fertilizer and as an ingredient in feed for ruminants; in urea-formaldehyde resins; as a solubilizing agent for proteins and starch; as an ingredient in softeners for cellulose products; as an acid-acceptor; and in medicine.

Knowledge of the chemistry of urea has been accumulating since the latter part of the 18th century. In 1773, an alkaline nitrogenous substance that yielded carbonic acid and ammonia on bacterial fermentation was extracted from the solid residue of evaporated urine by Rouelle. In 1821, pure urea was isolated from urine by Prout, and in 1828 urea was synthesized by Wöhler from ammonia and cyanic acid. This famous synthesis of Wöhler's is sometimes cited as the first synthesis of an organic compound from inorganic compounds. Uric acid (*q.v.*), first reported in 1778 as a constituent of urine, was first synthesized by fusing urea with glycine, NH_2CH_2COOH, and later by heating urea with 3,3,3-trichlorolactic acid.

Physical and Chemical Properties

Constants. M.p., 132.7°C. (dec.); d_4^{20}, 1.335; n_D^{20}, 1.484 and 1.602; heat of fusion, $\Delta H = -5.78$ to -6.00 cal./g.; heat of combustion, 2531 cal./g.; heat of solution in water, -57.8 cal./g.; free energy of formation at 25°C., $-47{,}120$ cal./mole (solid); sp. heat at 20°C., 0.320 cal./(g.)(°C.) (4). See also Vol. **1**, pp. 743, 744.

TABLE I. Solubility of Urea in Water.

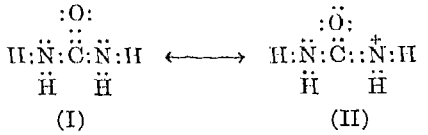
Temp., °C.	Soly., g./100 g. soln.	Approx. sp.gr. of satd. soln.
20	52.0	1.146
40	62.5	1.165
60	71.5	1.180
80	80.0	1.193
100	88.0	1.204

TABLE II. Solubility of Urea in Alcohols at 30°C.

Alcohol	Soly., g./100 g. alcohol
Methyl	27.7
Ethyl	7.2
n-Propyl	3.6
Isobutyl	2.3
Isoamyl	1.6

Urea sublimes under vacuum at temperatures just below and up to its melting point. It is readily soluble in water (see Table I), alcohols (see Table II), and liquid ammonia. It is only slightly soluble in ethyl ether, ethyl acetate, and pyridine at room temperature. Urea is somewhat hygroscopic and absorbs moisture from the atmosphere.

Reactions (4). Although in most of its reactions urea behaves as though it had the formula NH_2CONH_2, it reacts with alkylating agents to give *O*-alkyl derivatives of the hypothetical enol form, $HN{=}C(OH)NH_2$, called *pseudourea* or *isourea*. The alkylation reactions, its action as a monoacid base to form salts having the cation $H_2N^+{=}C(OH)NH_2$, and certain physical properties of urea have led to the assumption that it is a resonance hybrid of two zwitter ions (II and the same structure with the charge on the other nitrogen) and probably also the carbamide structure (I):



(I) (II)

Urea undergoes a number of reactions on heating above its melting point. At 150–160°C. it first decomposes to yield ammonia, ammonium cyanate, NH_4OCN, and biuret, $HN(CONH_2)_2$. As the temperature is raised further, other products including the cyclic compounds cyanuric acid, $C_3N_3(OH)_3$, and ammelide, $NH_2C_3(OH)_2$, are formed. See also Vol. **4**, pp. 681–82.

Neutral solutions of urea are hydrolyzed very slowly in the absence of microorganisms to ammonia and carbon dioxide:

$$NH_2CONH_2 + H_2O \longrightarrow 2\,NH_3 + CO_2$$

Hydrolysis is hastened by higher temperatures, addition of either acids or bases, presence of the enzyme urease (see Vol. **5**, p. 759), or increase in the concentration of urea. No hydrolysis inhibitors are known.

Hypochlorite, hypobromite, or acid permanganate solutions oxidize urea to carbon

dioxide, nitrogen, and water. Chloroureas, prepared by the action of chlorine or hypochlorites on well-cooled solutions of urea, serve as a route to hydrazine (*q.v.*).

Urea, acting as a monobasic compound, forms salts with mineral acids, such as nitric, sulfuric, phosphoric, and hydrochloric, and with some organic acids, notably oxalic and acetic.

In liquid ammonia, urea reacts with alkali metals or alkali metal amides to form metallic salts such as $NH_2CONHNa$ and $CO(NHNa)_2$. Aqueous solutions of urea act on silver oxide to form the disilver derivative, $CO(NHAg)_2$. A dimercury derivative can be similarly prepared.

Ureasulfonic acids, such as $CO(NHSO_3H)_2$, have been prepared. Urea reacts with sulfur trioxide to yield the monosulfonic acid, $NH_2CONHSO_3H$, which reacts further with sulfuric acid to give sulfamic acid (*q.v.*), NH_2SO_3H. Sulfamic acid is also synthesized by the reaction of urea with chlorosulfonic acid.

Urea forms crystalline complexes with a large variety of inorganic and straight-chain aliphatic organic compounds (see under "Uses"). Among the inorganic compounds are: sodium chloride, ammonium chloride, and salts of copper, silver, gold, magnesium, zinc, cadmium, chromium, aluminum, mercury, and lead. With hydrogen peroxide urea forms a crystalline compound, $CO(NH_2)_2.H_2O_2$, which is stable below 80°C. (see Vol. **10**, p. 82).

The primary condensation product between two moles of formaldehyde and one of urea is dimethylolurea, $CO(NHCH_2OH)_2$ (see under "Derivatives").

Urea reacts with malonic acid (*q.v.*) or its diesters to form barbituric acid (*q.v.*) (malonylurea). Derivatives of barbituric acid are widely used as sedatives.

Ethyl alcohol reacts with urea at elevated temperature and pressure, or with urea nitrate, $NH_2CONH_2.HNO_3$, and sodium nitrite, to form urethan (*q.v.*), $NH_2COOC_2H_5$.

Manufacture

Urea is produced commercially by synthesis from ammonia and carbon dioxide:

$$2\,NH_3 + CO_2 \longrightarrow NH_2CONH_2 + H_2O$$

As an emergency measure in the U.S. and Canada during World War I, and for some time in Europe, the hydrolysis of calcium cyanamide was employed (4):

$$CaCN_2 + 3\,H_2O \longrightarrow NH_2CONH_2 + Ca(OH)_2$$

FROM AMMONIA AND CARBON DIOXIDE

The overall reaction may be considered to be a combination of the following reversible reactions (10) (see also *Ammonolysis*, Vol. **1**, p. 840):

$$2\,NH_3 + CO_2 \rightleftharpoons NH_2COONH_4$$

$$NH_2COONH_4 \rightleftharpoons NH_2CONH_2 + H_2O$$

The ammonium carbamate, NH_2COONH_4, is an important, unstable intermediate in this synthesis of urea. The solid carbamate is readily formed, with substantial liberation of heat, so long as the partial pressure of ammonia plus carbon dioxide exceeds the dissociation pressure of ammonium carbamate (about 1 atm. at 60°C., and about 7 atm. at 100°C.). The further reaction of ammonium carbamate to form urea takes place in the liquid or solid phases only, the equilibrium conversion being reduced by the presence of water. A quantitative thermodynamic study of these

reversible reactions has been made by Frejacques (7). The reactions involved do not require the intentional addition of a catalyst.

Purification of Raw Materials (10). It is necessary to remove sulfur compounds, oxygen, and inerts from the feed. Sulfur compounds are often associated with carbon dioxide, and are said to be undesirable. The presence of oxygen in the reactor leads to corrosion problems and is undesirable. Inert gases affect the process economics by (*1*) requiring a higher total pressure to attain a given degree of equilibrium conversion, and (*2*) necessitating the taking of a gas purge at some point in the process, with consequent possible loss of reactants. See also *Ammonia*.

Synthesis (10). Urea can be produced economically in a "once-through" synthesis if there is other use for the unreacted ammonia, and if there is a sufficient supply of carbon dioxide. In such installations, the off-gas ammonia from urea synthesis can be converted to nitric acid, ammonium sulfate, ammonium nitrate, etc., and the off-gas carbon dioxide wasted.

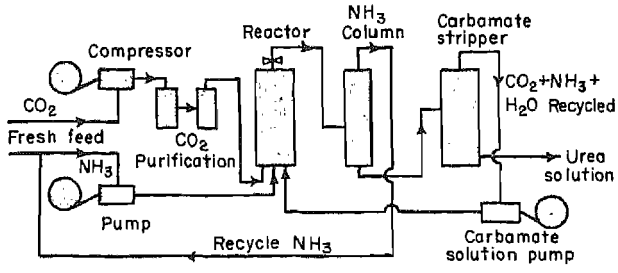


Fig. 1. Solution recycle process (10).

In many cases, however, a urea plant must be self-contained, and the unreacted off-gas must be recycled. To accomplish this, four types of manufacturing processes have been used commercially, the processes differing chiefly in the manner in which the unreacted ammonia and carbon dioxide are recycled to the reactor.

The problem encountered in recycle is potential deposition of solid ammonium carbamate when the recycle gas is compressed. This has been solved in four ways: (*1*) by recycling ammonium carbamate in water solution; (*2*) by recycling an oil slurry of ammonium carbamate; (*3*) by maintaining the recycle gases at so high a temperature that ammonium carbamate cannot form; (*4*) by separation of the ammonia from carbon dioxide and recycling either the ammonia alone (if there is an excess of carbon dioxide available) or both components in relatively pure form. The four types of processes are described below. Flow diagrams are shown in Figures 1–4.

Solution Recycle Process. Portions of this process are covered by patents assigned to du Pont (15,16). A variant of this process has been developed by Montecatini in Italy, and is available through the M. W. Kellogg Company.

Recycling of ammonia and carbon dioxide as an aqueous solution of ammonium carbamate tends to reduce conversion to urea because of the presence of so much water in the system. This is compensated for by using high reactor temperatures (200–210°C.) to give a higher reaction rate and by maintaining an excess of 3–5 moles of ammonia. These conditions require, in turn, very high reactor pressures (about 400 atm.). Because of the high excess ammonia in the system, it is possible to strip most of it away from the reaction solution and recycle it as anhydrous liquid ammonia.

Overall yields are reported to be well over 90% on ammonia and carbon dioxide. A conversion per pass of 70% on carbon dioxide (compared with normal 40–45% at 170°C.) reduces compression requirements somewhat.

Plant investment is high because of the high operating pressure and the necessity for using silver-lined reaction equipment. The higher temperature increases the corrosion problems; in spite of the silver-lined equipment, corrosion troubles have been experienced.

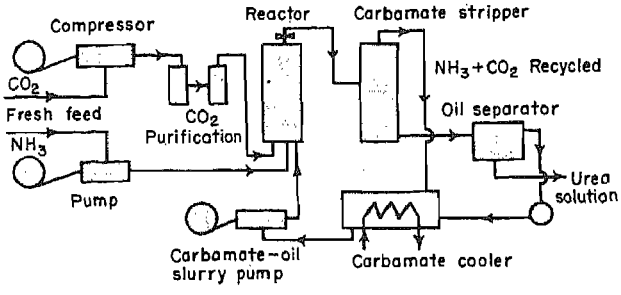


Fig. 2. Oil slurry recycle process (10).

Oil-Slurry Recycle Process. This process was developed by Pechiney in France and is available through Foster-Wheeler Corporation. This process is being used by John Deere & Co. and the Grace Chemical Co.

The recycle gas stream is conducted under a pressure of a few atmospheres to internally cooled and agitated vessels, through which mineral oil is circulated. Here

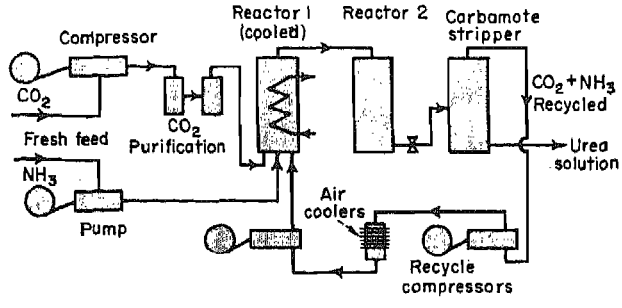


Fig. 3. Hot gas recycle process (10).

the ammonia and carbon dioxide readily condense to solid carbamate, which is dispersed in the oil. This crystal slurry (temperature not higher than 45°C.) is then pumped into the reactor, which operates at 180°C. and 200 atm. pressure. Apart from its function as carrying vehicle for the carbamate, the oil also helps control the reactor temperature by taking up liberated heat, which is partially released in the stripper.

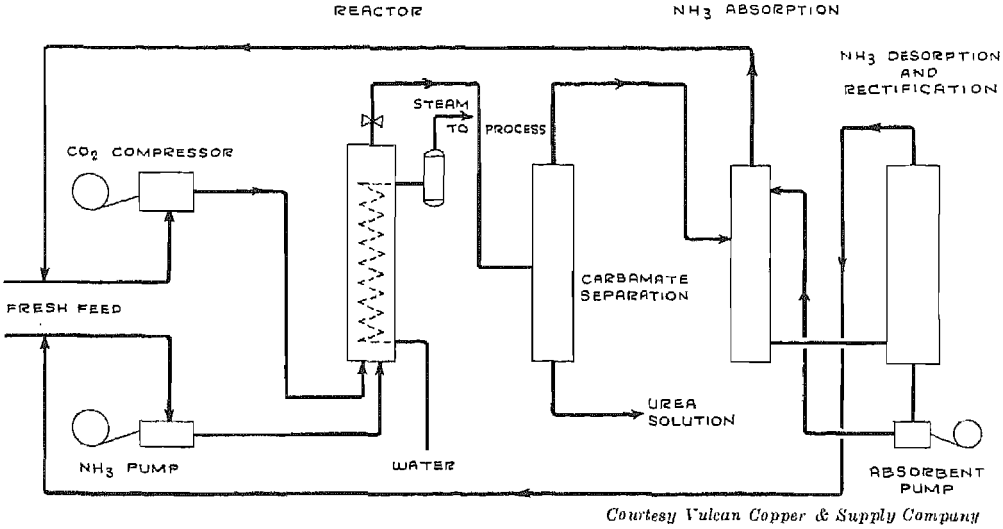
A yield of about 93% on both ammonia and carbon dioxide is claimed without purge recovery and with a carbon dioxide feed of 98% purity. With a carbon dioxide purity of 99.5%, yield may go up to better than 96% on ammonia. Corrosive conditions (high temperature) occur only in the reactor, which is a lead-lined shell without

any internal cooling device. The presence of oil is claimed to reduce corrosion in the absence of oxygen.

Hot-Gas Recirculation Process. I. G. Farbenindustrie at Oppau compressed the recycle gas mixture in five stages up to 120–130 atm. in uncooled compressors. Between compression stages air cooling was provided; this, however, had to be very carefully controlled so that solid carbamate would not be formed. Recycle of hot gases imposed a greater cooling load on the reaction system than would be the case when feeding cold carbon dioxide and liquid ammonia, and required the use of a two-stage reactor to control the reaction at the desired temperature of 160–170 °C. Heat was carried off by water boiling inside the tubes under regulated pressure.

Overall yield of urea was reported to be 93% on ammonia and 83.5% on carbon dioxide.

The first reactor stage was packed with a number of lead-covered cooling tubes. The recycle compression system also contributed to an obviously high plant invest-



Courtesy Vulcan Copper & Supply Company

Fig. 4. Inventa process.

ment. Operation of this plant was difficult and required an exorbitant maintenance. This process may now be considered outdated.

Ammonia and Carbon Dioxide Recycle Process (1,5,6). Although several different methods have been proposed for accomplishing the separation of unreacted ammonia and carbon dioxide to permit recycling as pure components, the first that achieved commercial success is the ammonia absorption process of Inventa A.-G. of Lucerne, Switzerland. This process, operating at the plant of Holzverzuckerungs A.-G. in Ems, Switzerland, is offered by The Vulcan Copper and Supply Company in the U.S. Another process, using an absorbent for carbon dioxide to achieve the separation, has been developed by Chemical Construction Corporation at the Sumitomi Chemical Company plant in Japan.

Purification of Crude. Crude urea contains biuret which is formed to some extent whenever urea is heated in the neighborhood of its melting point or above. The final product will contain varying amounts of biuret, depending on the purification process.

Crystal Urea. Crystal urea is the highest purity urea available in ton quantities and is packaged in 100-lb paper bags. It is obtained by crystallization from solution and centrifugation and, as produced in the U.S., contains a minimum of biuret (not more than about 0.05% biuret) and other impurities.

Urea, U.S.P., is prepared from crystal urea.

Shotted Urea. To provide the greater ease of handling required by some end uses, crude urea is made available in various granular and "shotted" forms. Shotting is presumably accomplished in an operation similar to the shotting of lead.

Economic Aspects

In 1951, it was estimated that the investment in a plant producing about 100 tons/day would be between $12,000 and $20,000 per daily ton (10).

Table III gives production of industrial (crystal) urea for some of the years from 1935 to 1951. The market price early in 1955 for industrial urea (crystal—46% N) was $0.06–0.065/lb., and for the U.S.P. grade $0.12/lb.

TABLE III. U.S. Production and Imports of Urea (Fertilizer Compositions Excluded).

Year	Production, tons	Imports, tons
1935[a]	800	3,935
1939[a]	10,000	820
1940[a]	15,000	—
1941[a]	25,000	—
1943[a]	38,350	—
1947[a]	47,000	1,266
1948[a]	> 60,000	9,521
1949[b]	250,000	—
1950[b]	300,000	—
1951[b]	220,000	—

[a] Reference (12); fertilizer compositions excluded.

[b] Reference (5a); including fertilizer compositions, which accounted for about 10% of the total.

In the U.S., E. I. du Pont de Nemours & Company, Inc. began production of synthetic urea in 1935 and Allied Chemical and Dye Corporation about 1949. The Deere Company and Grace Chemical Company began production of urea early in 1955.

Specifications and Analysis

One manufacturer of crystal urea specifies that its product should be a crystalline solid, uniformly white in color, and free from brown lumps and other foreign material. It should meet the following specifications: pH of a 10% solution at 20°C., 7.0–9.8; water, 0.5% maximum; ash, 35 p.p.m. maximum; iron, 2 p.p.m. maximum; free ammonia, 40 p.p.m. maximum; color, A.P.H.A. (see Vol. 4, p. 248) (10 g. in 100 ml. methanol), 10 maximum; turbidity, A.P.H.A. (50 g. in 100 ml. water), 30 p.p.m. maximum.

Standard analytical methods are used for the determinations of the pH and ash content. Water is determined by the Karl Fischer reagent method. The amount of iron present is determined spectrophotometrically by converting the iron to salts and

measuring the pink color formed upon the addition of thioglycolic acid. Free ammonia is ascertained by titration with 0.01 *N* hydrochloric acid using methyl red as indicator. Turbidity is measured spectrophotometrically.

Other determinations that may be made by the manufacturer are copper content (spectrophotometrically), formaldehyde color (A.P.H.A.), buffer strength, alkalinity, ammonium salts, and nitrogen content (Kjeldahl method). This last is the official method of the Association of Official Agricultural Chemists.

Uses (3)

Among the most important uses of urea is as an ingredient in urea-formaldehyde resins and plastics (see *Amino resins and plastics*). These resins are widely used: as adhesives (*q.v.*) for plywood (*q.v.*), veneers, and composition boards (see *Wallboard*); as a molding powder; and as finishes or additives for textiles (see *Textile technology*, Vol. **13,** p. 901), paper, and metals. For 1953 the U.S. Tariff Commission reported for urea-formaldehyde-type resins a production of 194,387,000 lb. and sales of 178,975,000 lb. (both on the dry basis) at a unit value of $0.25/lb.

Urea can also be used in the preparation of barbituric acid (*q.v.*), caffeine (*q.v.*), ethyleneurea (2-imidazolidinone), $NH.CO.NH.CH_2CH_2$, hydrazine (*q.v.*), melamine, sulfamic acid (*q.v.*), guanidine, and urea peroxide.

Urea is used in the manufacture of fertilizers (see Vol. **6,** p. 392). It has many advantages over other nitrogenous plant foods since it is a highly concentrated source of available nitrogen (46.6% N), has good leach resistance in the soil, leaves no soil residues, and is noncorrosive to application equipment. It is also applied to the leaves of plants by spraying of an aqueous solution.

When fed to ruminant animals (especially cattle) together with a source of fermentable carbohydrate, urea supplies the nitrogen needed for the biochemical synthesis of proteins by the microorganisms of the rumen. (See also Vol. **6,** p. 311.) Urea can be used as a source of nitrogen for yeast in fermentation processes.

Urea is used as an ingredient in softeners for a wide variety of products based on cellulose, including glassine and other papers, cellophane, cellulose sponge and yarn, and wood. With wood, urea serves to retard end-checking of boards during drying, and facilitates bending.

Addition of urea to solutions of casein, animal glue, gelatin, and starch causes a reduction in viscosity and permits the use of higher concentrations of active ingredient in such uses as sizes and adhesives for paper products. Urea has a synergistic effect on gelatin-sulfonated oil sizes for textiles.

Urea is used in some deodorants to minimize tendering of fabrics by aluminum sulfate; in some explosives to prevent accidental detonation which may occur due to gradual build-up of acids; and in dentrifices, in an attempt to minimize decay resulting from acid-producing organisms.

The formation by urea of crystalline adducts ("inclusion complexes") with straight-chain aliphatic compounds (9,13) is of importance in the resolution of certain mixtures, as, for example, in the separation of normal alkanes or olefins from petroleum fractions by contact with saturated aqueous solutions of urea. The straight-chain compound fills the interstices normally present in urea crystals, and, when the complex is separated and placed in water, the urea dissolves, releasing the straight-chain compound.

The complexes all seem to have the same melting point as urea, and none studied

so far are stable above 133 °C. The stability of the urea complexes seems to vary directly with the chain length and inversely with the vapor pressure of the included compound.

In general, urea will not form complexes with branched-chain or cyclic compounds, unless they contain a long enough straight chain somewhere in the molecule, and the branched or cyclic portion is not too large. *Thiourea*, however, which also forms inclusion complexes, will generally form complexes only with branched-chain and cycloaliphatic compounds and not with straight-chain compounds, aromatics, or terpenes (13). See also refs. (2,8,14,17,18,19).

Urea is also used as a complexing agent in the fractionation of wool grease (*q.v.*), especially in the separation of cholesterol.

Urea is used medicinally as a diuretic (*q.v.*); as a synergist for certain sulfa drugs; and in veterinary medicine, with sulfur, to control coccidiosis of poultry. It promotes the healing of some wounds. Urea derivatives of organic arsenic compounds are used as amebacides (*q.v.*). Combinations of urea with stibanilic acid, p-$NH_2C_6H_4SbO_3N_2$, such as *urea-stibamine* (Stiburea), have been recommended for the treatment of kala-azar (see Vol. **2**, p. 68). Certain derivatives of urea, such as Afridol Violet, have been tested for use as trypanocides (*q.v.*).

Miscellaneous applications include its use with phosphoric acid to render paper and textiles fire-resistant (see Vol. **6**, p. 553); as an ingredient in fire-resistant paints; in skin creams and lotions to improve feel; as a component of soldering fluxes; and in a mixture with biuret as a blowing agent for foamed rubber (see Vol. **11**, p. 888).

Bibliography

(1) Anon., *Chem. Eng.*, **59**, No. 11, 219–22 (1952).
(2) Bailey, W. A., Jr., Bannerot, R. A., Fetterly, L. C., and Smith, A. G., *Ind. Eng. Chem.*, **43**, 2125–29 (1951).
(3) Berliner, J. F. T., *Chem. Ind.*, **38**, No. 3, 237–42 (1936) (100 refs.).
(4) Berliner, J. F. T., *Ind. Eng. Chem.*, **28**, 517–22 (1936) (88 refs.).
(5) Bland, W. F., *Petroleum Processing*, **7**, 1457–60 (1952).
(5a) *Chemical Economics Handbook*, Department of Business and Industrial Economics, Stanford Research Institute.
(6) Cook, L. H., *Chem. Eng. Progress*, **50**, No. 7, 327–31 (1954).
(7) Frejacques, M., *Chimie & industrie*, **60**, No. 1, 22 (1948).
(8) Hepp, J. H., Box, E. O., Jr., and Ray, G. C., *Ind. Eng. Chem.*, **45**, 112–15 (1953).
(9) Marschner, R. F., *Chem. Eng. News*, **33**, 494 (1955).
(10) Rooseboom, A., *Chem. Eng.*, **58**, No. 3, 111–14 (1951).
(11) Sidgwick, N. V., *The Organic Chemistry of Nitrogen*, new ed., Oxford Univ. Press, London, 1937, pp. 275–92.
(12) Skeen, J. R., *Chem. Eng.*, **56**, No. 6, 319 (1949).
(13) Swern, D., *Ind. Eng. Chem.*, **47**, 216 (1955).
(14) Zimmerschied, W. J., Dinerstein, R. A., Weitkamp, A. W., and Marschner, R. F., *Ind. Eng. Chem.*, **42**, 1300–6 (1950).
(15) U.S. Pat. 1,898,093 (Feb. 21, 1933), F. W. Miller (to Du Pont).
(16) U.S. Pat. 2,116,881 (May 10, 1938), H. W. De Ropp (to Du Pont).
(17) U.S. Pat. 2,640,051 (May 26, 1953), C. S. Lynch (to Phillips Petroleum Co.).
(18) U.S. Pat. 2,658,060 (Nov. 3, 1953), G. B. Arnold and L. Kovac (to the Texas Co.).
(19) U.S. Pat. 2,658,887 (Nov. 10, 1953), G. B. Arnold, J. K. Truitt, and H. V. Hess (to the Texas Co.).

F. A. WOLFF AND D. J. O'FLYNN

Derivatives

UREA SALTS

Urea nitrate, $NH_2CONH_2.HNO_3$, is one of the best known of these salts. It is formed on the addition of an aqueous urea solution to excess aqueous nitric acid, whereupon the salt precipitates in well-formed crystals and in nearly quantitative yield. The insolubility of this salt in nitric acid solution is so marked that precipitation of urea as the nitrate has been used in semiquantitative analysis.

On treatment of urea nitrate with cold, concentrated sulfuric acid, *nitrourea* is formed:

$$NH_2CONH_2.HNO_3 \xrightarrow{H_2SO_4} NH_2CONHNO_2 + H_2O$$

Electrolytic reduction of nitrourea yields semicarbazide, $NH_2CONHNH_2$ (see *Hydrazine and its derivatives*, Vol. **7**, p. 586). Nitrourea is more strongly acidic than acetic acid. It condenses readily with primary or secondary amines to form *N*-substituted ureas:

$$NH_2CONHNO_2 + RNH_2 \longrightarrow NH_2CONHR + N_2O + H_2O$$

Urea phosphate, $NH_2CONH_2.H_3PO_4$, has been proposed as a fertilizer (18,19).

Metal salts of urea and complexes of urea with inorganic salts have been mentioned under "Physical and Chemical Properties." Urea peroxide, $NH_2CONH_2.H_2O_2$, is described in Vol. **10**, p. 82.

URETS

Biuret, $NH_2CONHCONH_2$ (see also Vol. **1**, p. 743), is one of the thermal degradation products of urea, but forms in poor yield. Better yields are afforded by passing cyanic acid vapor into molten urea, and still better by the treatment of urea with thionyl chloride, $SOCl_2$. This last method also yields small amounts of *triuret*, $NH_2CONHCONHCONH_2$.

Biuret gives a violet coloration when treated with copper sulfate and excess alkali. This "biuret reaction" is useful in the detection of polypeptides and proteins (see Vol. **11**, p. 228).

Biuret has been proposed as a starting material in making amino resins (see Vol. **1**, p. 752) but has certain undesirable properties and has achieved no known commercial success in this application (15).

ALKYL- AND ARYLUREAS

Both *N*- and *O*-substituted alkyl- and arylureas are known, the *O*-derivatives being referred to as iso- or pseudoureas (see p. 459). ***N*-Substituted ureas** are prepared by the action of cyanic acid on an amine, yielding mono- or asymmetrical disubstitution products; by the action of phosgene, $COCl_2$, on secondary amines to give the *N,N'*-tetrasubstituted urea; and by treating urea itself, at appropriate temperatures and in a suitable solvent, with primary amines, forming symmetrical disubstituted ureas.

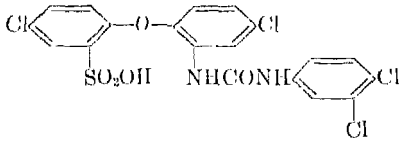
Carbanilide (*N,N'*-diphenylurea), $C_6H_5NHCONHC_6H_5$, is prepared by the reaction of aniline with urea, of aniline with phosgene, or of aniline with phenyl isocyanate. For the properties of carbanilide see *Amides*, Vol. **1**, p. 669.

Pseudoureas, $NH{=}C(OR)NH_2$, are most conveniently prepared by the addition of an alcohol or phenol to cyanamide, $CNNH_2$, in the presence of dry hydrogen chlo-

ride (11). More stringent conditions are required with phenols than with alcohols (3,20). *O*-Methylpseudourea has also been prepared by treating urea with methyl sulfate.

As a class, the alkyl- and arylureas are of little commercial importance today. However, 3-(*p*-chlorophenyl)-1,1-dimethylurea (CMU), $ClC_6H_4NHCON(CH_3)_2$, synthesized by the reaction of *p*-chlorophenyl isocyanate with dimethylamine, m.p. 169.8–170.4°C., and other *N*-alkylurea derivatives such as 3-phenyl-1,1-dimethylurea (PDU) are used as weed killers (*q.v.*).

A series of *N,N'*-diarylurea derivatives and their preparation were patented (21), for use as mothproofing agents. The most important member of this series is a diphenylurea derivative, Mitin FF (10), from the condensation of the appropriately substituted 2-aminodiphenyl ether and *N*-(3,4-dichlorophenyl)carbamoyl chloride:



Other suggested applications for one or another of these substituted ureas have included uses in sweetening agents, as waterproofing and shrinkproofing agents for textiles, as humectants, and in pharmaceutical applications. Treatment of the lower *N,N'*-dialkylureas with phenyl isocyanate affords a convenient method for preparing the lower alkyl isocyanates (see also *Phosgene (organic isocyanates)*).

$$RNHCONHR + 2\,C_6H_5NCO \longrightarrow 2\,RNCO + C_6H_5NHCONHC_6H_5$$

METHYLOLUREAS

Dimethylolurea (1,3-bis(hydroxymethyl)urea, DMU), $CO(NHCH_2OH)_2$, formula weight 120.1, m.p. 126°C., heat of solution −25 cal./g. Dimethylolurea is available commercially as a white chalky solid (87–90% dimethylolurea) with a formaldehyde odor; m.p. 85–90°C.; d^{20} 1.32–1.35; pH of a 10% aqueous solution 8.0–8.5. The price early in 1955 was $0.20–0.24½/lb.

The solubility of the commercial product in water at room temperatures is 15–20% by weight. Solubility increases rapidly with temperature until 80–85°C., where dimethylolurea is completely miscible with water. Unless the compound has been partially resinified by prolonged heating, a concentrated solution will deposit dimethylolurea on cooling. It is essentially insoluble at room temperature in most organic solvents, including methanol. However, in the presence of acid catalysts, dimethylolurea dissolves in alcohols with the formation of the corresponding ethers.

When the pH of a dimethylolurea solution is lowered, an insoluble, resinous precipitate will form at a rate depending on the acidity and the temperature of the solution. Precipitation is almost immediate at pH 3, and may be delayed for weeks at pH 7 and room temperature.

Heating concentrated solutions of dimethylolurea near 100°C. will cause the slow formation of viscous, sticky, resin sirups, which remain fluid at room temperature. The rate of resinification is primarily dependent on the pH. At too low a pH value, immediate gelation occurs, and addition of further acid, even at room temperature, will cause the condensation of the sirup to an insoluble resinous solid. See also *Amino resins and plastics*, Vol. 1, p. 7-47.

Dimethylolurea has no specific toxic characteristics of its own, but precautions applicable to the handling of formaldehyde should be used.

Dimethylolurea should be stored in a cool location, and prolonged storage should be avoided as it tends to become less soluble in water upon aging. However, if the material is to be stored for a period of months and a highly water-soluble product is required, it is desirable to maintain it at 40°F. or below.

Dimethylolurea has been used in the production of thermosetting molding resins, hot- or cold-setting resin adhesives, resin finishes, impregnation of textiles, increasing the water resistance and hardness of proteins, starches, and polyvinyl alcohol; as a hardening agent for plaster, etc., as an intermediate in organic synthesis, and in the impregnation of wood to increase its hardness.

Methylolureas of lower formaldehyde-urea ratios than in dimethylolurea are readily prepared by dissolving urea and dimethylolurea together in water. For example, *monomethylolurea*, $HOCH_2NHCONH_2$, is formed on dissolving 2 parts of dimethylolurea with 1 part of urea. As the ratio of formaldehyde to urea is reduced, the product becomes increasingly soluble in water; for example, monomethylolurea is soluble to the extent of 40–45% by weight. These methylolureas, however, are just as readily resinified as dimethylolurea or insolubilized by heating or by adding acids.

So-called *alcoholated ureas* or alcohol-modified resins used as coating materials are formed by reaction of urea with formaldehyde in the presence of an alcohol. They are complex derivatives in which the formaldehyde joins urea to the alcohol and also urea to urea. The portion of the polymer with the grouping —$CONCH_2OR$ (an ether of a methylolurea) can be called an *N*-alkoxymethylurea derivative; for example, *N*-butoxymethylurea ("*n*-butylated urea"). See also Vol. **1**, p. 758.

ACYLUREAS, UREIDES

The acylureas of monobasic acids may be prepared by the action of the acid chloride or anhydride on urea. Prolonged heating with an excess of the chloride leads to the formation of the *N,N'*-diacyl derivative.

Certain of the class have found application as wetting agents, in dye applications, in the preparation of resins, and as pharmaceuticals. Haloacetylureas are sternutators or lacrimators.

Cyclic ureides, the acylureas of dibasic acids, include uric acid (*q.v.*) (found in mammalian and avian excreta) and the important family of the barbiturates (*q.v.*). Riboflavin (*q.v.*) (vitamin B_2), biotin (*q.v.*), and caffeine (*q.v.*) are among the cyclic compounds containing the urea nucleus that have biological significance.

AMMONO ANALOGS

The ammono analog of urea is guanidine (*q.v.*), $NH_2C(=NH)NH_2$. Guanylurea (dicyandiamidine), $NH_2CONHC(=NH)NH_2$, and biguanide, $NH_2C(=NH)NHC(=NH)NH_2$, are the aquo-ammono and ammono analogs of biuret. Both are prepared from dicyandiamide, $NH_2C(=NH)NHCN$ (see Vol. **4**, 674). Many derivatives of guanylurea and of biguanide have been examined for antimalarial activity, and 1-(*p*-chlorophenyl)-5-isopropylbiguanide (Paludrine) has shown a pronounced effectiveness in this application (see Vol. **8**, p. 671).

THIO ANALOGS, THIOUREAS

Thiourea (thiocarbamide), NH_2CSNH_2, occurs as colorless crystals whose structure has been examined by Wyckoff and Corey (17). It has no true melting point,

but, when heated rapidly, melts at about 178–80°C. Thiourea has been found in nature in the laburnum shrub, and as the product of certain fungus cultures.

Thiourea is moderately soluble in water. At 25°C., a saturated solution contains 14.2 g. thiourea per 100 g. in water, 11.9 g. in methanol, and about 4 g. in ethyl alcohol. It is considerably more soluble in liquid ammonia (64.9 g. per 100 g. saturated solution at 30°C.), and is also soluble in pyridine (12.5 g. per 100 g. solvent at 20–25°C.; 41.2 g. per 100 g. 50% aqueous pyridine at 20–25°C.) (13).

Chemically, thiourea and its derivatives undergo many of the reactions of the ureas, and, especially in patent specifications, the thioureas are commonly cited as being equivalent to the ureas. In practice, owing largely to economic considerations, the thioureas have not enjoyed a comparable acceptance.

The chemical structure of thiourea is best represented as an equilibrium of the keto and enol forms:

$$NH_2CSNH_2 \rightleftharpoons NH_2C(SH)=NH$$

The enol form, particularly in the case of its derivatives, is known as *pseudothiourea* or *isothiourea*.

On heating, thiourea first undergoes reversion to the equilibrium mixture with ammonium thiocyanate (see below). Heating above the melting point in a sealed tube leads to extensive rearrangement, and substantial quantities of guanidine thiocyanate are found in the reaction products.

Thiourea forms salts, both with acids and bases, and numerous examples of complex compounds of thiourea with metal salts are known. Like urea, thiourea forms adducts or occlusion compounds with certain organic materials (4) (see p. 466).

Treatment of thiourea with heavy metal oxides, such as mercury oxide, in aqueous medium, removes the elements of hydrogen sulfide and yields cyanamide, $CNNH_2$. This is one of the favored methods for obtaining substituted cyanamides, starting from the appropriately substituted thiourea.

Alkylating agents lead to the formation of the *S*-substituted or pseudothioureas. Thus methyl sulfate and thiourea form *S*-methylpseudothiourea sulfate:

$$(CH_3)_2SO_4 + 2\ NH_2CSNH_2 \longrightarrow (NH_2C(SCH_3)=NH)_2.H_2SO_4$$

This reaction, conducted in aqueous solution, spontaneously forms the methyl hydrogen sulfate of *S*-methylpseudothiourea as the first step, the reaction then being completed by boiling. The decomposition of *S*-methylpseudothiourea by hot alkali is useful for the preparation of methyl mercaptan, the side-reaction product being cyanamide, which polymerizes at once to dicyandiamide (1):

$$NH_2C(SCH_3)=NH \xrightarrow[\text{alkali}]{\text{hot aq.}} CH_3SH + CNNH_2$$

$$2\ CNNH_2 \longrightarrow NH_2C(=NH)NHCN$$

Acylating agents, such as acid chlorides or anhydrides, react with thiourea to give the *N*-acyl derivative:

$$NH_2CSNH_2 + RCOCl \longrightarrow RCONHCSNH_2 + HCl$$

Phenyl isocyanate will condense with thiourea to give a phenylthiobiuret:

$$C_6H_5NCO + H_2NCSNH_2 \longrightarrow C_6H_5NHCONHCSNH_2$$

Thiourea condenses with aldehydes and with alkylene oxides to form *N*-hydroxyalkyl derivatives. The condensation products with formaldehyde lead to resins.

Thiourea is isomeric with ammonium thiocyanate and, similarly to the urea–ammonium cyanate relationship, is formed upon heating the thiocyanate to 140–80°C.:

$$NH_4SCN \rightleftharpoons NH_2CSNH_2$$

The equilibrium favors ammonium thiocyanate, the more so at higher temperatures, lying at 28.1% thiourea at 140°C. and 21.8% at 180°C. It is the establishment of this equilibrium that leads to the uncertain melting points reported for thiourea. See also Vol. **4**, p. 737.

A more effective method of preparing thiourea is the addition of hydrogen sulfide to cyanamide in aqueous solution under mildly alkaline conditions. The use of moderate pressures increases the solubility of hydrogen sulfide, and hence favors the reaction:

$$CNNH_2 + H_2S \longrightarrow NH_2CSNH_2$$

Thiourea, because of its moderate solubility, is easily recovered from the reaction mixture. Thiourea can also be prepared from calcium cyanide, ammonia, and hydrogen sulfide. See Vol. **1**, p. 744.

Technical-grade thiourea is sold in 75-lb. paper bags. The price early in 1955 was $0.40–0.42/lb.

Thiourea is reportedly more toxic to plant life than is urea and hence is not a suitable fertilizer material. It is of a low order of toxicity to animal life, but is not without hazard (11a). Prolonged administrations inhibit the functioning of the thyroid gland (1a). The toxic dose for rats and rabbits is about 10 grams per kilogram body weight. The onset of toxic results is quite sudden. Ingestion (rabbits) of 9 g./kg. (stomach tube) resulted in no ill effects; 10 g./kg. in 50% deaths; 11 g./kg. in 100% deaths (9).

Thiourea was once a regular and important constituent of the urea-formaldehyde resins (see *Amino resins and plastics*), owing to the then relatively lower cost of thiourea compared to urea. When this situation was reversed, the disadvantages of thiourea in many resin applications led to its near abandonment in this field. A relatively new proposal is the use of thiourea resins for flameproofing nylon (2).

Uses other than in resins, either proposed or practiced, include applications in the textile industry in the weighting of silk and as a dye bath adjuvant; in photography as a gold or sepia toner; in agriculture, where thiourea hastens the sprouting of dormant tubers and also has pesticidal properties; in the metal trades as a pickling inhibitor and in cleaning and plating baths; in the preparation of nonglare mirrors; and as a raw material in chemical syntheses, as the synthesis of sulfathiazole.

Substituted thioureas have been prepared in great numbers, but few have achieved technical importance. Various thiourea derivatives have been found effective as tuberculostatic agents (see p. 348) and as antithyroid agents (see p. 134). Schroeder has prepared an excellent review of the preparation and biological properties of the thioureas (12), and Curphey has summarized their uses in organic synthesis (5).

Thiocarbanilide (*N,N'*-diphenylthiourea), $C_6H_5NHCSNHC_6H_5$, enjoyed a one-time vogue as a vulcanization accelerator in rubber, but has been superseded by more powerful and less "scorchy" materials. Heating thiocarbanilide with carbon disulfide and sulfur yields mercaptobenzothiazole (Captax), one of the widely used accelerators (6). (See also Vol. **11**, p. 873.) Thiocarbanilide has also had some use as a flotation agent (see Vol. **6**, p. 610).

α-Naphthylthiourea (Antu), $C_{10}H_7NHCSNH_2$, is an economic poison with specific toxicity toward the common rat (see Vol. **10**, p. 873).

Salts of thiourea and pseudothiourea compounds are sometimes named as "thiuronium" or "isothiuronium" compounds, in analogy with the naming of onium compounds (see Vol. **9**, p. 592), although these names have not yet been fully accepted. *Thiuronium* has been applied both to the *N*-substituted thiourea and pseudothiourea salts and to the *S*-substituted pseudothiourea salts, but *isothiuronium* only to the pseudothiourea compounds. Thus the compound $NH_2C(SCH_3)=NH.HCl$ might be named 2-methyl-2-thiopseudourea hydrochloride (*C.A.*), *S*-methylthiuronium chloride, *S*-methylisothiuronium chloride, methylisothiuronium chloride, or methylpseudothiourea hydrochloride. Similarly the compound $NH_2CSNHCH_3.HCl$ might be named 1-methyl-2-thiourea hydrochloride (*C.A.*), *N*-methylthiuronium chloride, methylthiuronium chloride, or methylthiourea hydrochloride.

Bibliography

(1) Arndt, F., *Ber.*, **54**, 2236–42 (1921).
(1a) Astwood, E. B., *Harvey Lectures*, **Ser. 40**, 195–235 (1945).
(2) Axtmann, R. C., and Sweet, A. T., *Textile World*, **101** (3), 130, 216 (1951).
(3) Battegay, M., and Silbermann, H., *Compt. rend.*, **194**, 988–90 (1932).
(4) Cramer, F., *Angew. Chem.*, **64**, 437–47 (1952).
(5) Curphey, E. G., *Chem. Products*, **18**, 98–100 (1955).
(6) Davis, C. C., and Blake, J. T., eds., *The Chemistry and Technology of Rubber*, Reinhold, N.Y., 1937.
(7) Degering, E. F., *An Outline of Organic Nitrogen Compounds*, University Lithoprinters, Ypsilanti, Mich., 1950.
(8) Fieser, L. F., and Fieser, Mary A., *Organic Chemistry*, 2d ed., Heath, Boston, 1950.
(9) Flinn, F. B., and Geary, J. M., *Contribs. Boyce Thompson Inst.*, **11**, 241–7 (1940).
(10) Läuger, P. v., Martin, H., and Müller, P., *Helv. Chim. Acta*, **27**, 892–928 (1944).
(11) McKee, R. H., *Am. Chem. J.*, **26**, 209–64 (1901).
(11a) Pfankuch, E., in Houben, J., *Fortschritte der Heilstoffchemie*, Vol. II, Pt. 1, Berlin, 1930, pp. 1283–84. (Photo-lithoprinted by Edwards, Ann Arbor, 1946.)
(12) Schroeder, Dorothy C., *Chem. Revs.*, **55**, 181–228 (1955).
(13) Seidell, 3d ed., Vol. 2, 1941, pp. 41–3.
(14) Sidgwick, N. V., *The Organic Chemistry of Nitrogen*, new ed., Oxford University Press, 1937.
(15) Simons, J. K., *Papers presented at the Boston meeting, Division of Paint, Varnish and Plastics Chemistry, American Chemical Society, April*, 1951, p. 221.
(16) Williams, H. E., *Cyanogen Compounds*, 2d ed., Arnold, London, 1948.
(17) Wyckoff, R. W. G., and Corey, R. B., *Z. Krist.*, **81**, 386–95 (1932).
(18) Ger. Pat. 286,491 (Nov. 8, 1915), Badische Anilin- u. Soda-Fabrik.
(19) U.S. Pat. 1,440,056 (Dec. 26, 1922), F. Clarkson and J. M. Braham.
(20) U.S. Pat. 2,039,514 (May 5, 1936), M. Battegay (to Calco Chemical Co.).
(21) U.S. Pat. 2,311,062 (Feb. 16, 1943), H. Martin (to J. R. Geigy Co.).

C. E. FUNK, JR.

UREA-FORMALDEHYDE RESINS. See *Amino resins and plastics.*

UREASE. See *Enzymes*, Vol. **5**, p. 759.

UREIDES. See *Urea (derivatives)*, p. 469.

URETHANS

The term urethan (urethane) has sometimes been used to designate the esters, more particularly the ethyl esters, of carbamic acid (the monoamide of carbonic acid), NH_2COOH, and its *N*-substituted derivatives, $RR'NCOOH$. The urethans are typified by urethan (ethyl carbamate), $NH_2COOC_2H_5$. The urethan names are now being replaced by more systematic names, for example, $CH_3CH_2CH_2NHCOOC_2H_5$ is named ethyl propylcarbamate (ethyl *N*-propylcarbamate) instead of propylurethan, and $C_6H_5NHCOOC_2H_5$ is named ethyl phenylcarbamate or ethyl carbanilate instead of phenylurethan.

In general, derivatives of carbamic acid have been widely employed in the plastics field, as monomers, comonomers, plasticizers, and fiber and molding resins; in textile finishing; in agricultural chemicals, as weed killers (*q.v.*), fungicides, and insecticides; and in medicine, as hypnotics and sedatives, anticonvulsants, miotics, anesthetics, and antiseptics.

Derivatives of *dithiocarbamic acid*, NH_2CSSH, sometimes called thiourethans, are used as fungicides (see Vol. **6**, p. 987) and in the rubber industry as vulcanization accelerators (see *Rubber chemicals*).

Urethan

PHYSICAL AND CHEMICAL PROPERTIES

Urethan, U.S.P. XIV (ethyl carbamate), $NH_2COOC_2H_5$, is a white crystalline solid, m.p. 49–50°C., b.p. 182–84°C., d_4^{48} 1.0599, d_4^{80} 1.0280, d. (of the crystals) 0.8 (approx.). Urethan has a vapor pressure of 54 mm. at 103°C., 108 mm. at 120.7°C., and 697 mm. at 177°C. It sublimes readily and tends to absorb moisture from the air. At 25°C., it is very soluble in water and in the lower aliphatic alcohols, ketones, ethers, esters, and chlorinated hydrocarbons; somewhat less soluble in aromatic hydrocarbons; and relatively insoluble in aliphatic hydrocarbons. At temperatures near or above its melting point urethan becomes very soluble in nearly all the common organic solvents.

Inasmuch as urethan is an ester amide of carbonic acid, it exhibits the reactions normally shown by both groupings. It is readily hydrolyzed in aqueous solution by acids to yield ethyl alcohol, carbon dioxide, and an ammonium salt, and by bases to yield ethyl alcohol, ammonia, and a carbonate. Basic hydrolysis in alcoholic potassium hydroxide, however, produces ethyl alcohol and potassium cyanate. Halogenation, and especially chlorination, of cold aqueous solutions, produces *N*-halo- or *N,N*-dihalourethans depending upon the ratios of the reactants:

$$NH_2COOC_2H_5 + Cl_2 \longrightarrow ClNHCOOC_2H_5 \xrightarrow{Cl_2} Cl_2NCOOC_2H_5$$

The sodium derivative of urethan may readily be prepared by treating urethan with sodium metal in dry ether (1):

$$NH_2COOC_2H_5 + Na \xrightarrow{\text{dry ether}} NaNHCOOC_2H_5 + \tfrac{1}{2}H_2$$

With urethan and higher alcohols in the presence of catalysts, such as aluminum isopropoxide, ester interchange takes place (8):

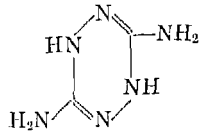
$$NH_2COOC_2H_5 + ROH \xrightarrow{Al(OCH(CH_3)_2)_3} NH_2COOR + C_2H_5OH$$

Acyl derivatives of urethan may be formed directly by its reaction with esters (5), acid anhydrides, or acid chlorides (2):

$$NH_2COOC_2H_5 + RCOCl \longrightarrow RCONHCOOC_2H_5$$

The acyl derivatives may also be prepared by the reaction of acid chlorides with the sodium derivatives of urethan. Urethan reacts with hydrazine at elevated temperatures and pressures to produce 3,6-diamino-1,4-dihydro-*s*-tetrazine (16):

$$NH_2COOC_2H_5 + H_2NNH_2.H_2O \longrightarrow$$



With aldehydes urethan forms *N*-methylol (*N*-hydroxymethyl) compounds under mildly alkaline conditions, alkylidenebisurethans under mildly acidic conditions, and polymeric products under consecutive alkaline and then acidic conditions (8):

$$NH_2COOC_2H_5 + RCHO \xrightarrow[\text{alkali}]{\text{mild}} HOCHRNHCOOC_2H_5$$

$$NH_2COOC_2H_5 + RCHO \xrightarrow[\text{acid}]{\text{mild}} RCH(NHCOOC_2H_5)_2$$

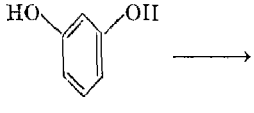
$$x\ NH_2COOC_2H_5 + x\ RCHO \xrightarrow[(2)\ \text{acid}]{(1)\ \text{alkali}} C_2H_5OOCNH[CHRN(COOC_2H_5)]_{x-1}CHROH$$

Ethyl nitrite reacts with urethan in cold concentrated sulfuric acid to yield *N*-nitrourethan:

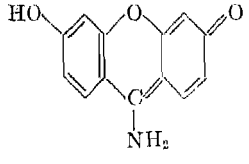
$$NH_2COOC_2H_5 + C_2H_5ONO \xrightarrow[0°C.]{\text{concd. } H_2SO_4} O_2NNHCOOC_2H_5$$

which can be used as an intermediate for the preparation of *N*-nitrosourethan ($ONNHCOOC_2H_5$), ethyl carbazate ($NH_2NHCOOC_2H_5$), nitramide (NH_2NO_2, see Vol. **9**, p. 410), mono- and dialkylnitramines ($RNHNO_2$ and $RR'NNO_2$), and hydrazines (9). Condensation of resorcinol with urethan results in the formation of 6-hydroxy-9-amino-3*H*-isoxanthen-3-one, a yellow dye related to fluorescein and suitable for silks and wools (11):

$$NH_2COOC_2H_5 +$$



$$\longrightarrow$$



With a number of inorganic salts urethan forms mixed salts, such as $H_2NCOOC_2H_5.CaI_2$ and $H_2NCOOC_2H_5.2KBr$.

PREPARATION AND MANUFACTURE

Urethan is manufactured from ethyl chloroformate, $ClCOOC_2H_5$ (see *Carbonic esters and chloroformic esters*) and ammonia. Materials of construction for the portions of the equipment handling the chloroformate should be acid-resistant, preferably glass- or porcelain-lined or of Karbate, although they may be lead-lined. The reactor itself should be resistant to the action of ammonium hydroxide; stainless steel is satisfactory for this vessel and for subsequent refining equipment.

The reactor is charged with ammonium hydroxide (approximately 25% concentration), and ethyl chloroformate is added at such a rate that reaction temperatures can be kept below 40°C. by external cooling. When ethyl chloroformate equivalent to slightly less than one-half of the ammonia has been added, the simultaneous addition of 30% aqueous sodium hydroxide is also started. Additions of the chloroformate and caustic solution are thereafter metered so that a slight excess of chloroformate is maintained in the reactor. At the completion of the additions, feeds are so controlled that there is no residual chloroformate or caustic and only a small amount of ammonium chloride. Essentially the reaction during the first half of the process is as shown in equation (1) and during the second half as shown in equation (2).

$$ClCOOC_2H_5 + 2\,NH_4OH \longrightarrow NH_2COOC_2H_5 + NH_4Cl + 2\,H_2O \quad (1)$$

$$ClCOOC_2H_5 + NH_4Cl + 2\,NaOH \longrightarrow NH_2COOC_2H_5 + 2\,NaCl + 2\,H_2O \quad (2)$$

When the reaction is complete, the aqueous salt layer is separated from the molten crude urethan layer, which is transferred to distillation equipment. The salt layer is chilled to 32°F., whereupon most of the dissolved urethan is crystallized and can be removed by filtration. The wet filter cake is also transferred to the distillation equipment. The urethan is then distilled at reduced pressure (approx. 50 mm.), and the molten distillate is crystallized in a rotary crystallizer, sieved, and packaged. Packages should be airtight, since even crystalline urethan has an appreciable vapor pressure, sublimes readily, and shows a tendency to absorb moisture from the air.

Alternatively, urethan may be synthesized in a variety of ways: by the reaction of ethyl alcohol with carbamoyl chloride, cyanic acid, urea (*q.v.*) at elevated pressure, or urea nitrate and sodium nitrite:

$$NH_2COCl + C_2H_5OH \longrightarrow NH_2COOC_2H_5 + HCl$$

$$HOCN + C_2H_5OH \longrightarrow NH_2COOC_2H_5$$

$$NH_2CONH_2 + C_2H_5OH \longrightarrow NH_2COOC_2H_5 + NH_3$$

$$NH_2CONH_2.HNO_3 + C_2H_5OH \xrightarrow{NaNO_2} NH_2COOC_2H_5 + N_2$$

or by the ammonolysis of diethyl carbonate:

$$(C_2H_5O)_2CO + NH_3 \longrightarrow NH_2COOC_2H_5 + C_2H_5OH$$

The commercial product (urethane, U.S.P.), m.p. 48–50°C., contains at least 98% urethan, and may contain up to 2% water. It is combustible and not flammable, and has a flash point over 80°F. Urethan is available in fiber drums (250 lb. net) at $1.50/lb. There are no shipping regulations.

USES

Urethan has been used medicinally as a mild hypnotic (see Vol. 7, p. 777), sedative, and antispasmodic, in a treatment for leukemia and related blood diseases, as an antagonist against the action of certain stimulants, and as an antidote for strychnine, resorcinol, and picrotoxin poisoning. It has been used as an ingredient of nonluminous heating candles, astringent cosmetic preparations, and quinine sclerosing solutions, and has been employed as an intermediate in the preparation of certain dyes. Urethan-aldehyde condensation products have been used as latent flavor-developing substances in packaged foods. Urethan has also found use as an anesthetic for laboratory animals, and in the sedation of fish during transportation.

Other Urethans

PHYSICAL AND CHEMICAL PROPERTIES

Many carbamates have been reported in the chemical literature and Table I shows the physical properties of some representative compounds of simpler structural types. The carbamates of lower molecular weights resemble urethan itself with regard to solubility characteristics in that they are relatively soluble in the more polar organic solvents and less soluble in the nonpolar ones. As with other types of organic compounds, the solubilities of the higher-molecular-weight members are more a function of the substituting groups than of the carbamate functional group itself.

TABLE I. Properties of Some Carbamates.

Carbamate	Structure	*Formula* weight	M.p., °C.	B.p., °C.
Methyl	NH_2COOCH_3	75.07	54	177, 82_{14}
Ethyl	$NH_2COOC_2H_5$	89.10	49–50	184
n-Propyl	$NH_2COOCH_2CH_2CH_3$	103.12	60–61	195
Isopropyl	$NH_2COOCH(CH_3)_2$	103.12	95–95.5	—
n-Butyl	$NH_2COOCH_2CH_2CH_2CH_3$	117.15	53–54	203–4 (d.)
sec-Butyl	$NH_2COOCH(CH_3)C_2H_5$	117.15	94	—
Isobutyl	$NH_2COOCH_2CH(CH_3)_2$	117.15	55	206–7
n-Amyl (pentyl)	$NH_2COO(CH_2)_4CH_3$	131.17	55.5	—
2-Ethylbutyl	$NH_2COOCH_2CH(C_2H_5)_2$	145.20	81	—
2-Ethylhexyl	$NH_2COOCH_2CH(C_2H_5)(CH_2)_3CH_3$	173.25	42.5	—
Allyl	$NH_2COOCH_2CH{=}CH_2$	101.10	21	204
Phenyl	$NH_2COOC_6H_5$	137.13	147–148.5	—
Benzyl	$NH_2COOCH_2C_6H_5$	151.16	86	220 (d.)
Trichloroethyl	$NH_2COOCH_2CCl_3$	192.45	64–65	—
Ethyl *N*-methyl-[a]	$CH_3NHCOOC_2H_5$	103.22	—	170
Ethyl *N*-ethyl-[b]	$C_2H_5NHCOOC_2H_5$	117.25	—	176
Ethyl *N*-phenyl-	$C_6H_5NHCOOC_2H_5$	165.19	49–50	237 (d.)
Isopropyl *N*-phenyl-	$C_6H_5NHCOOCH(CH_3)_2$	179.21	87–88	—
Methyl *N,N*-dimethyl-[c]	$(CH_3)_2NCOOCH_3$	103.12	—	131
Ethyl *N,N*-dimethyl-[d]	$(CH_3)_2NCOOC_2H_5$	117.15	—	147
Ethyl *N,N*-diethyl-[e]	$(C_2H_5)_2NCOOC_2H_5$	145.20	—	167–69; 63_{14}
Ethyl *N,N*-diphenyl-	$(C_6H_5)_2NCOOC_2H_5$	241.28	72	360

[a] $n_D^{18.0}$ 1.4200; d_{19} 1.009.
[b] d_4^{20} 0.981.
[c] d^{15} 1.012.
[d] d^{18} 0.9725.
[e] n_D^{20} 1.4206; d_4^{20} 0.9276.

In addition to the reactions cited for urethan, variously substituted carbamates undergo numerous other reactions as well. *N*-Monosubstituted carbamates react readily with nitrous acid to form *N*-nitroso compounds. This reaction is employed to prepare alkyl *N*-nitrosoalkylcarbamates, which despite their pronounced vesicant action are used as intermediates in the preparation of diazoalkanes, for example:

$$CH_3NHCOOR' \xrightarrow{HONO} CH_3N(NO)COOR' \xrightarrow{KOH} CH_2N_2$$

In a similar fashion, *N*-nitrocarbamates may be prepared by the action of fuming nitric acid on *N*-monosubstituted carbamates in acetic anhydride solution. If the substituents of the carbamate include aryl groups, they are also nitrated under these conditions.

Under certain conditions, *N*-monosubstituted carbamates can be converted to the corresponding isocyanates. This is usually accomplished by heating the carbamates in the presence of phosphorus pentachloride or phosphorus pentoxide:

$$RNHCOOR' \xrightarrow{P_2O_5} RNCO + (R'O)_3PO$$

However, heating the carbamates in the absence of a catalyst or dehydrating agent has also been reported to be effective.

Under alkaline conditions, 2- or 3-haloalkyl carbamates may be cyclized to the corresponding oxazolidinones or oxazinones:

$$RNHCOOCH_2CHXR' \xrightarrow{\text{alkali}} RN.CHR'.CH_2.O.CO$$

Unsaturated carbamates, especially those with the unsaturation in a terminal position, may be polymerized with or without comonomers in the presence of typical vinyl polymerization catalysts, such as acyl peroxides or alkali peroxydisulfates, to form polymeric products.

PREPARATION AND MANUFACTURE

Most carbamates can be readily prepared by reactions similar to those used above for urethan, as well as by other reactions that are not specifically adaptable to urethan itself.

Isocyanates react easily with hydroxyl compounds of practically all types to yield carbamates:

$$RNCO + R'OH \longrightarrow RNHCOOR'$$

The Hofmann hypohalite degradations of amides (13), as well as the Curtius rearrangement of azides (*q.v.*) (12) and the Lossen rearrangement of hydroxamic acid derivatives (14), have been demonstrated to go through isocyanate intermediates. If these reactions are conducted in the presence of alcohols the isocyanate intermediates are converted to carbamates.

$$RCONH_2 \xrightarrow[(2)\ NaOH,\ CH_3OH]{(1)\ Br_2} RNHCOOCH_3$$

$$RCOCl + NaN_3 \longrightarrow RCON_3 \xrightarrow[\text{heat}]{R'OH} RNHCOOR'$$

$$RCONHOOCR' + R''OH \xrightarrow{\text{heat}} RNHCOOR'' + R'COOH$$

The manufacture of carbamates may be accomplished by the method described for urethan, in which an amine is substituted for ammonia, and the reaction may, if desired, be carried out under anhydrous conditions in an appropriate organic solvent.

Although many isocyanates are difficult to store conveniently and safely because of the ease with which they polymerize or are destroyed by reaction with moisture, they are sometimes used commercially as carbamate intermediates, for example, to improve the hardness and water and alkali resistance of certain alkyd resins, in the formation of foamed infusible rigid plastics, in the curing of polyester rubbers (3) (see Vol. **11**, p. 845), and in the preparation of polyurethan. See also Vol. **10**, p. 401.

USES

Carbamates have found use in a wide variety of biological applications. They have been used as enzyme inhibitors and miotics, as antipyretics, diuretics, and anti-

septics; as anthelmintics and anticonvulsants; as weed killers (7), insecticides, and insect repellents (6); fungicides (17); and snailicides.

The demonstration that urethan, and more particularly certain substituted carbamates, reversibly inhibited or inactivated the enzyme cholinesterase (see Vol. **13,** p. 28) was one of the first examples of specific enzyme competition. Physostigmine, U.S.P. XIV, neostigmine, U.S.P. XIV, N.N.R., and the carbamic acid ester of choline itself, carbachol, U.S.P. XIV (see Vol. **3,** p. 926), are examples of the substituted carbamates.

Perhaps the most important single application of carbamates to date is the use of certain alkyl *N*-phenyl- or *N*-(substituted-phenyl)carbamates as weed killers (*q.v.*). Two compounds of this type, isopropyl *N*-phenylcarbamate (IPC) and isopropyl *N*-(*m*-chlorophenyl)carbamate (CIPC), have attained large-scale commercial uses.

Carbamates have found a number of interesting applications in the plastics industry as resins, plasticizers, monomers, antioxidants, and stabilizers. By the reaction of diisocyanates with glycols the so-called "polyurethans" may be prepared. One such polyurethan, Perlon U (Igamid U), was prepared commercially in Germany by the reaction of hexamethylene diisocyanate with 1,4-butanediol in a mixed solvent of mono- and dichlorobenzenes. This process required very careful adjustments of the molecular proportions of the diisocyanate and glycol to avoid breaking of the polymer chain, and the use of equivalent molecular amounts of these reactants led to a polymer having an average molecular weight of about 10,000, which melted rather sharply at 180–185°C.:

$$HO(CH_2)_4OH + OCN(CH_2)_6NCO \longrightarrow [NH(CH_2)_6NHCOO(CH_2)_4OOC]_n$$

and found use in the extrusion of bristles, spinning of filaments, and in injection molding. This resin has outstanding water resistance in comparison with the nylon or caprolactam polyamides (see *Polyamides*) and is also reputed to have better electrical properties, greater resistance to acids, superior hardness, and a much lower susceptibility to oxidative degradation than the other polyamides. Perhaps the major disadvantage of these resins is their inferior thermal stability, which prevents their use or processing at temperatures above about 220°C. (4,10).

Another interesting plastics application, in which the formation of carbamate linkages plays an important part, is in the formation of rigid plastic foams (Moltoprens) in which, for example, a diisocyanate (Desmodur) is treated with a polyester (Desmophen) of a dicarboxylic acid and a trihydroxy alcohol, which still contains free hydroxyl and carboxylic groups. The isocyanate first reacts with the hydroxyl groups to form carbamate bridges, and then with the carboxyl groups to give carboxamide linkages together with the simultaneous elimination of carbon dioxide. As the reactions continue, the plastic mass becomes increasingly tough, and the liberated carbon dioxide causes it to swell like a dough. In the earlier stages of this reaction the plastic mass can be molded at moderate temperatures but, with continued reaction, enlargement, and reticulation, it becomes rigid and infusible. This process makes possible the manufacture of low-density foamed plastics of much higher strengths than were previously known. They currently find application in the manufacture of lightweight, high-strength, structural parts for airplanes, whereby the reaction mixture may be poured into the interior of structural parts made of thin metallic sheets and allowed to expand in place to fill the shell. The resulting parts have excellent dimensional strength (4).

By the selection of appropriate raw materials and reaction conditions, it is also possible to produce foams of varying degree of softness. Foams similar in resilience to the rubber latex foams are easily prepared and have numerous advantages over the rubber foams. They are expected to find a wide and varied market (3a).

Another application in which formation of carbamate-type linkages often plays an important part is illustrated by the isocyanate-containing adhesives. They are suitable for bonding a great variety of surfaces to one another and have found application in bonding many synthetic textile fibers to elastomers, elastomers to wood or to metal, wood to wood or to metal or porcelain, or many plastics to any of these materials. These adhesives are usually mixtures of difunctional isocyanates with di- or trifunctional acids and hydroxylic compounds. The isocyanates react readily with any active hydrogen atoms forming, when the hydrogen is a part of a hydroxyl group, a carbamate linkage. It has been suggested that the adhesion demonstrated by these adhesives results primarily because of the great reactivity of the isocyanate group, which, for example, when used to bond another material to a metallic surface, will even react with hydrous oxide films on the metal to produce a clean surface capable of forming either primary or secondary valence bonds. In addition, the isocyanates polymerize easily in the presence of a variety of substances to produce a network of triazine structures, which are chemically very stable and strongly bonded and serve to bridge the space between the substances to be joined.

In a somewhat similar fashion, polyester or polyurethan rubbers are formed by the addition of diisocyanates to glycol end-blocked polyesters where, by the formation of carbamate linkages, they serve to increase the length of the polymer chains. During later processing, further additions of diisocyanates or other materials cross-link and cure these lengthened polymers. The resultant rubbers (Vulcollan, Bayer; Adiprene B, duPont; Chemigum SL, Goodyear) as a group show remarkable abrasion resistance and also excellent resistance to oil, ozone, and aging (3). See also Vol. **11**, p. 845.

Polyurethan coatings based upon polyesters and modified isocyanates have found extensive application in Europe and are finding increasing use in this country for wire coatings and similar purposes, where their excellent strength, toughness, and chemical resistance are of advantage.

Other applications in the plastics industry which depend largely upon the reaction of isocyanates with hydroxylic compounds to form carbamate linkages include the treatment of phenol-formaldehyde resins with diisocyanates to improve alkali and water resistance and the treatment of protein and cellulose textiles to improve water resistance and dyeing properties.

Carbamates, especially *N*-nitrocarbamates, can be used as Diesel fuel additives. For example, it has been reported that by the addition of 1% of ethyl *N*-nitro-*N*-butylcarbamate the cetane number of a Diesel fuel may be raised from 39 to 50 (15).

Carbamates are also used for surface-active agents, selective solvents, dye intermediates, corrosion inhibitors, etc.

Bibliography

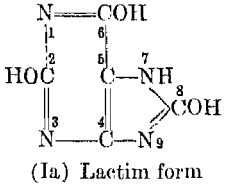
(1) Allen, C. F. H., and Bell, A., in Drake, *Organic Synthesis*, Wiley, N.Y., 1945, Vol. 24, p. 60.
(2) Basterfield, S., and Greig, M. E., *Can. J. Research*, 8, 450–57 (1933).
(3) Bayer, O., Müller, E., Petersen, S., Piepenbrink, H. F., and Windemuth, E., *Rubber Chem. Tech.*, 23, 812–35 (1950).

(3a) Bello, F., *Fortune*, **51**, No. 3, 110–113, 166, 169 (1955).
(4) DeBell, J. M., Goggin, W. C., and Gloor, W. E., *German Plastics Practice*, DeBell and Richardson, Springfield, Mass., 1946.
(5) Diels, O., and Heintzel, H., *Ber.*, **38**, 297 (1905).
(6) Ferguson, G. R., and Alexander, C. C., *J. Agr. Food Chem.*, **1**, 888–89 (1953).
(7) George, D. K., Moore, D. H., Brian, W. P., and Garman, J. A., *J. Agr. Food Chem.*, **2**, 356–63 (1954).
(8) Kraft, N. M., and Herbst, R. M., *J. Org. Chem.*, **10**, 483–97 (1945).
(9) Marlies, C. A., La Mer, V. K., and Greenspan, J., in Booth, *Inorganic Syntheses*, McGraw-Hill, N Y., 1939, Vol. **1**, pp. 68–74.
(10) Reynolds, R. J. W., "Polyamides, Polyesters, and Polyurethanes," in Hill, *Fibres from Synthetic Polymers*, Elsevier, N.Y., 1953, pp. 115–64.
(11) Sen, R. N., and Mukerji, A., *J. Indian Chem. Soc.*, **7**, 275–78 (1930).
(12) Smith, P. A. S., "The Curtius Reaction," in Adams, *Organic Reactions*, Wiley, N.Y., 1946, Vol. III, pp. 337–449.
(13) Wallis, E. S., and Lane, J. F., "The Hofmann Reaction," in Adams (see ref. 12), pp. 267–306.
(14) Yale, H. L., *Chem. Rev.*, **33**, 209–56 (1943).
(15) U.S. Pat. 2,438,452 (March 23, 1948), R. T. Pollock.
(16) U.S. Pat. 2,475,440 (July 5, 1949), H. A. Walter (to Monsanto).
(17) U.S. Pat. 2,537,690 (Jan. 9, 1951), D. T. Mowry and N. R. Piesbergen (to Monsanto).
(18) U.S. Pat. 2,537,691 (Jan. 9, 1951), D. T. Mowry and R. R. Morner (to Monsanto).

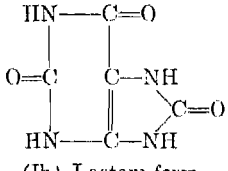
J. A. GARMAN

URIC ACID

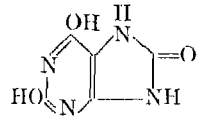
Uric acid (2,6,8(1*H*,3*H*,9*H*)-purinetrione), $C_5H_4N_4O_3$, formula weight 168.11, exists as white or yellowish-white, odorless, and tasteless crystals or powder. It is a member of the purines and xanthines (see Vol. **1**, p. 474) and exists in tautomeric forms, which probably are in equilibrium in solution (ref. 13, p. 765). It has usually been represented as the trienol (lactim form, (2,6,8-trihydroxypurine)) (Ia) or the triketone (lactam form, "2,6,8-trioxypurine") (Ib). The enol form accounts for the acidic properties. In this form, uric acid would be expected to be tribasic (ref. 13, p. 765), but it forms only two series of salts, the acid or primary salts, $MHC_5H_2N_4O_3$, and the normal, neutral, or secondary salts, $M_2C_5H_2N_4O_3$, probably owing to the very weak dissociation constant of the third hydrogen ion. The ketone form (Ib) accounts for its general lack of chemical reactivity, low solubility, etc. (15). The structural formulas for uric acid may be written as shown in (Ia) and (Ib) or as a benzenoid structure as in (Ic), shown as the "diolone" form or dibasic form as it is now sometimes written. See also *Heterocyclic compounds*, Vol. **7**, p. 440.



(Ia) Lactim form



(Ib) Lactam form



(Ic)

Von Scheele discovered uric acid in 1776 as a constituent of urine and bladder stones and named the substance "urine acid" as well as "bladder stone acid." Bergman made the same discovery at about the same time. Von Scheele described this substance in great detail, including its solubility and its behavior toward the various

mineral acids, especially nitric acid. In 1793 Fourcroy described the properties of uric acid in great detail and established its relationship with urea (*q.v.*). Other workers contributed immeasurably to the chemistry of uric acid, for example, Prout with his discovery of ammonium acid purpurate as a color test for uric acid (murexide test) and Brugnatelli with his preparation of alloxan by the action of nitric acid on uric acid. Formula (Ib) for uric acid was proposed by Medicus in 1875 and proved by Fischer as a result of his investigations into the preparation of the various methyl derivatives (ref. 27, pp. 88-91; 15). The first successful syntheses of uric acid, by fusing glycine, NH_2CH_2COOH, with urea and by heating 3,3,3-trichlorolactic acid, CCl_3CHOH-$COOH$, with urea, were reported by Horbaczewski in the 1880's. Wohler and Liebig, von Baeyer, Emil Fischer, Roosen, and others completed the monumental work on the properties and synthesis of uric acid.

Occurrence. Uric acid, usually in the form of its salts, is widespread in nature in both plants and animals. It is found in many seeds as well as other plant parts and is a constituent of the urine of all carnivorous animals, being formed from xanthine by the action of xanthine oxidase in the metabolism of purines and their derivatives, notably nucleic acids (*q.v.*). Uric acid is present in human urine to the extent of 0.3–2.0 g./day, varying with certain diets and with certain pathological conditions, such as arthritis and gout (sodium urate deposits in the joints in both diseases). In reptiles and birds uric acid is the chief end product of the metabolism of proteins as well as of purines. Thus excreta of certain reptiles may contain as high as 75% of almost pure ammonium urate. Chicken manures contain 2–3% ammonium urate, and certain bird excreta (guano) contain 10–20%.

Physical and Chemical Properties

Uric acid decomposes above 250°C. without melting, with evolution of hydrogen cyanide. It is soluble in glycerol, sulfuric acid (without decomposition), solutions of lithium carbonate, sodium acetate, and sodium phosphate, and very soluble in alkalies. It is practically insoluble in boiling water (1:2000) and insoluble in alcohol, ether, and chloroform.

Of the two series of salts formed, the acid alkali metal salts are less soluble in water than the normal salts. The acid piperazine salt and the lysidine (methylglyoxalidine) salts are much more soluble in water than the metallic acid or normal salts.

Like other purines, uric acid absorbs in the ultraviolet region. The maxima are dependent on the pH.

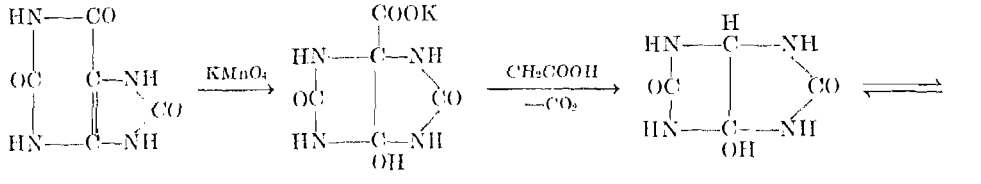
Uric acid has a pK_a of 5.7. It is stable to hydrolysis, but this stability decreases with increasing *N*-substitution. Alkali solutions are rather unstable. On dry distillation of uric acid, Scheele obtained carbon, ammonia, carbon dioxide, and cyanuric acid.

Uric acid is not easily affected by reducing substances, with a few exceptions; for example, Fischer and Ach prepared 6-thiouramil, $NH.CO.NH.CO.CH(NH_2).CS$, by heating uric acid with an ammonium sulfide solution at 160°C. Electrolytic reduction in sulfuric acid solution below 8°C. yields purone (dihydro-2,8-purinedione), $C_5H_8N_4O_2$, and, at 14–17°C., isopurone, $C_5H_8N_4O_2$ (in which the imidazole ring has been broken), along with purone, tetrahydrouric acid, and other products.

Uric acid is easily oxidized by a variety of compounds to give a wide variety of

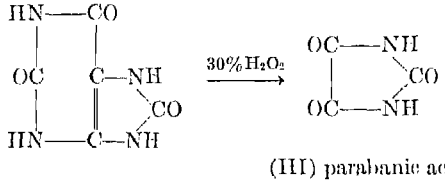
products. In general, alkaline oxidation attacks the pyrimidine ring and acid oxidation the imidazole ring.

SCHEME 1



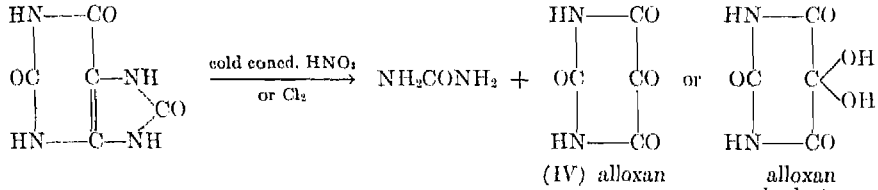
(II) allantoin — hydantoin

Oxidation with permanganate (6) yields allantoin (II), which will react with hydriodic acid to form hydantoin (for derivatives see "Hydantoin" under *Hypnotics and sedatives*, Vol. 7, p. 775) (see Scheme 1). Hydrogen peroxide oxidation gives different products according to the conditions of the reaction; one of the products is often allantoin (II). However, contrary to the general rule, when heating with 30% hydrogen peroxide (Perhydrol) under acid conditions the pyrimidine ring of uric acid is attacked to yield parabanic acid (III) with alloxan (IV) as an intermediate product:



(III) parabanic acid

Oxidation with cold concentrated nitric acid or with chlorine (12) yields alloxan (IV) and urea:

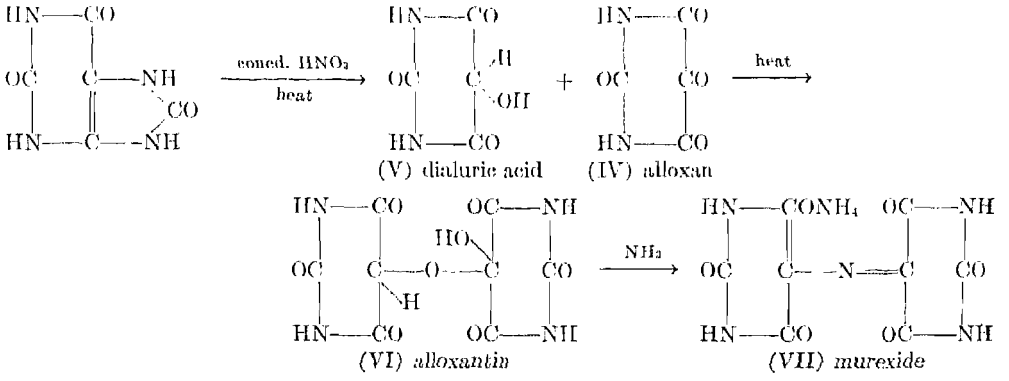


(IV) alloxan — alloxan hydrate

Heating with concentrated nitric acid (ref. 13, p. 767) yields dialuric acid (V) and alloxan (IV), both compounds on continued heating reacting further to give alloxantin (VI). On addition of ammonia, the purple-red murexide (VII) (acid ammonium purpurate) is obtained (8). (See Scheme 2.) With warm, very dilute nitric acid, alloxantin (VI) and urea are obtained directly.

Fischer and other investigators prepared various isomeric methyl (from mono to tetra) derivatives of uric acid (15; ref. 11, pp. 88–91). By heating uric acid with phosphorus oxychloride at 150–160°C., Fischer (ref. 11, p. 92) was able to produce

SCHEME 2



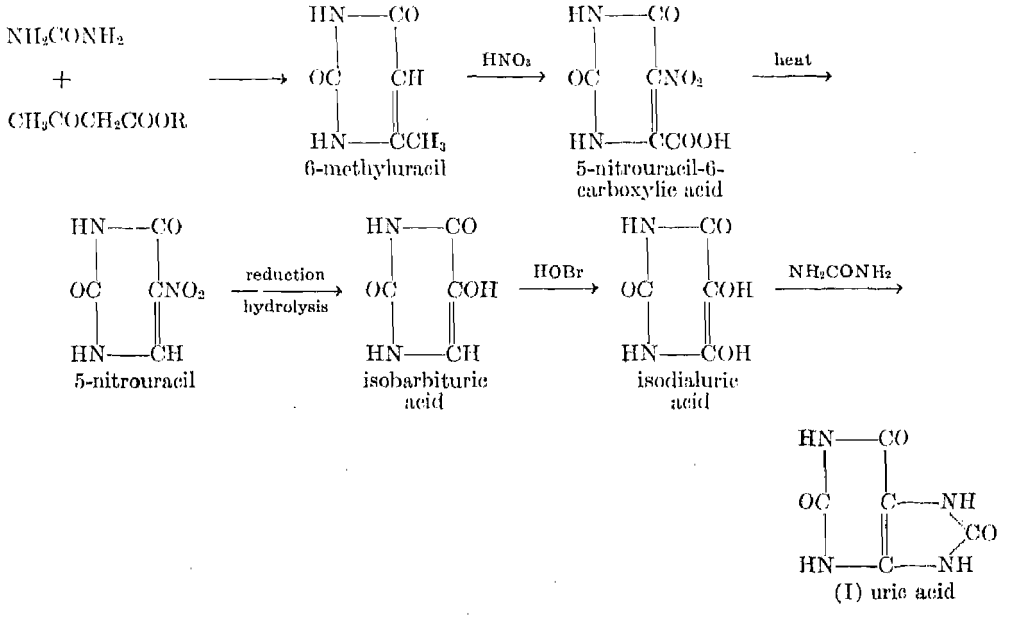
2,6,8-trichloropurine and 2,6-dichloro-8-hydroxypurine. Heating uric acid with formamide until completely dissolved yields, upon cooling, xanthine. Theophylline can be prepared similarly from 1,3-dimethyluric acid and formamide (18).

Preparation and Manufacture

Uric acid is produced by extraction from natural sources or synthetically.

Extraction from Natural Sources. Uric acid can be obtained by extracting either reptilian excreta or bird guano with sodium hydroxide, precipitating with ammonium chloride, and decomposing the precipitate with hydrochloric acid. The guano may also be treated with calcium carbonate in a strongly alkaline solution, and the free acid precipitated with hydrochloric acid. Bird guano is used as the commercial source of the acid.

SCHEME 3

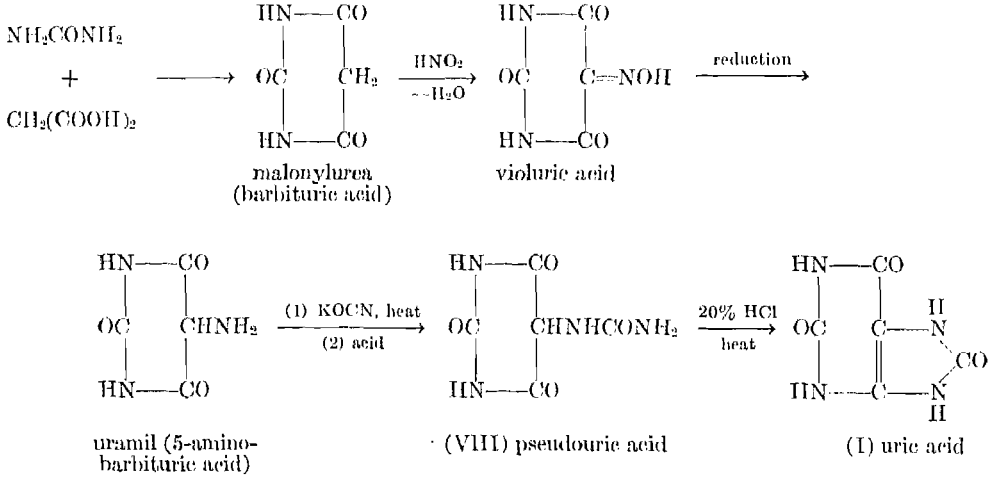


A slightly different procedure has been patented (17). Bird excrements are extracted with 8% aqueous sodium hydroxide and heated for 6–8 hr. at 80–100°C. with vigorous agitation. The solution is filtered, and the crude uric acid precipitated with sulfuric acid. The crude acid is then redissolved in 5–6% sodium hydroxide, and the solution evaporated to 20% of the original volume. Sodium urate crystallizes out of solution and is again dissolved in sodium hydroxide solution. The pure uric acid is precipitated with excess sulfuric acid.

Synthetic Methods. The thorough researches by Fischer and by Behrend and Roosen into the breakdown products (various stages of oxidation) of uric acid, and their possible combinations to produce uric acid, resulted in its successful synthesis. The Behrend and Roosen synthesis (ref. 11, p. 93) starts with urea and an acetoacetic ester (see Scheme 3).

Fischer, continuing the work of von Baeyer, succeeded in converting pseudouric acid (VIII) to uric acid by concentrating a solution of pseudouric acid in 20% hydrochloric acid solution. The work of von Baeyer and Fischer is combined in Scheme 4 to show the total synthesis of uric acid from urea and malonic acid by way of barbituric acid (*q.v.*).

SCHEME 4



Cavalieri and co-workers (4) report overall yields of only about 27% with the combined Baeyer and Fischer method. However, with certain modifications, an overall yield of 55% based on the urea used was obtained.

In a more recent synthesis of uric acid (5), 5-sulfoaminouracil (1,2,3,4-tetrahydro-2,4-dioxo-5-pyrimidinesulfamic acid), NH.CO.NH.CO.C(NHSO$_3$H):CH, is heated with urea at 190–200°C. for ½ hr. The melt is treated with hot water, yielding acid ammonium urate, which is dissolved in hot water containing the required amount of sodium hydroxide. The solution is clarified with carbon, and, while still hot, acidified with hydrochloric acid to give the free uric acid.

Uric acid is available in three grades: C.P., reagent, and technical (usually 90–95% pure). It is packaged in 1-lb. bottles and 5- to 100-lb. drums.

Analysis

Qualitative. *Murexide Test.* When uric acid is moistened with concentrated nitric acid and evaporated to dryness on a water bath, a purple-red color (resembling the dye from the sea snail *Murex*) develops on the addition of a few drops of ammonia. This test, however, is not restricted to uric acid, but will occur with other purines as well.

Quantitative. *In Urine.* (*1*) The Benedict and Francke method (2; ref. 13, p. 1172) utilizes the fact that solutions containing uric acid will develop a blue color, the intensity of which is proportional to the uric acid concentration, when arsenophosphotungstic acid (prepared from sodium tungstate, arsenic trioxide, phosphoric and hydrochloric acids) and sodium cyanide are added. This is a direct microchemical determination.

(*2*) In the Folin-Schaffer method (ref. 13, p. 1173), the uric acid is converted into ammonium urate, which is dissolved in hot sulfuric acid solution and then titrated with potassium permanganate solution.

In blood. Both methods described above can be used to determine the uric acid concentration in the blood. A more recent method for the determination of uric acid in blood uses a lithium carbonate reagent (10).

In Fruit Products. Tilden has described a paper chromatographic method (16).

Reagent Grade. The two methods described under urine can be used, or the nitrogen content can be determined by the Kjeldahl method.

Technical Grade. The Folin-Schaffer and Kjeldahl methods may be used.

Uses

Uric acid is used for the commercial preparation of allantoin, alloxan, alloxantin, parabanic acid, murexide, and other derivatives. Uric acid and its salts have been and are still being used on occasion in medicine. It has been used internally for edematous heart, pulmonary tuberculosis, persecution mania, etc., and also externally in gout. A 4% ointment of ammonium urate has been used in the treatment of chronic eczema, and also internally for coughs and grippe. Lithium acid urate is used as an antarthritic, and murexide is used as an organic indicator for the determination of calcium and other metal ions.

Derivatives

SALTS

Ammonium acid urate, $NH_4HC_5H_2N_4O_3$, formula weight 185.15, is a white crystalline powder, soluble in 1,600 parts cold water and more so in boiling water. It is soluble in alkalies or concentrated sulfuric acid, and is prepared by interaction of ammonia with uric acid.

Calcium urate (calcium acid urate), $CaH_2(C_5H_2N_4O_3)_2.2H_2O$, formula weight 410.32, is soluble in about 1,500 parts cold water. It is prepared by precipitating a potassium or sodium urate solution with calcium chloride.

Lithium acid urate, $LiHC_5H_2N_4O_3$, formula weight 174.05, is soluble in 380 parts cold or 39 parts boiling water. It is prepared by boiling uric acid with lithium carbonate.

Potassium urate (normal potassium urate), $K_2C_5H_2N_4O_3$, formula weight 244.30,

occurs in fine needles soluble in 44 parts cold water and 36 parts boiling water. It decomposes at high temperatures and is prepared in the same way as sodium urate.

Potassium acid urate, $KHC_5H_2N_4O_3$, formula weight 206.20, exists as a white amorphous powder soluble in 800 parts cold and in 80 parts boiling water. It is prepared in the same way as sodium acid urate.

Sodium urate (normal sodium urate), $Na_2C_5H_2N_4O_3$, formula weight 230.11, occurs as crystalline granules or a white crystalline powder soluble in about 77 parts cold and about 75 parts boiling water, and slightly soluble in alcohol. It decomposes at 150°C. and is prepared by suspending uric acid in a cold dilute sodium hydroxide solution and concentrating under a vacuum.

Sodium acid urate, $NaHC_5H_2N_4O_3$, formula weight 190.05, is a white powder soluble in 1,100–1,200 parts cold water and 125 parts boiling water. It is prepared by treating uric acid with a solution of sodium carbonate.

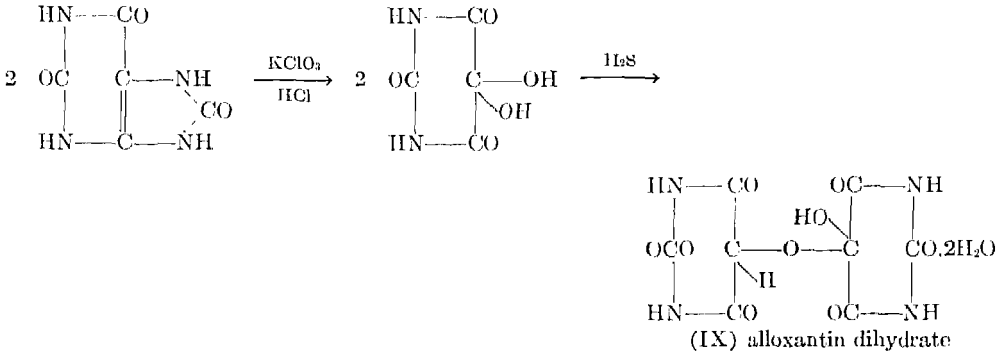
OTHER DERIVATIVES

Allantoin (5-ureidohydantoin, glyoxyldiureide) (II), $C_4H_6N_4O_3$, formula weight 158.08, is a white odorless powder, stable in air; m.p. approx. 228–235°C. (decompn.) (depending on method of determination). It is slowly soluble in about 200 parts cold water and about 25 parts boiling water. It dissolves, with decomposition, in solutions of alkali hydroxides. Allantoin occurs widely in plants and is excreted by almost all mammals, but not by anthropoid apes and man, as the end product of purine metabolism. It is formed by the action of the enzyme uricase on uric acid. It is produced synthetically in yields up to 75% by oxidizing uric acid with potassium permanganate in alkaline solution (6) (see p. 482). The commercial product, sold in drums, contains not less than 34.92% and not more than 35.45% of N, corresponding to not less than 98.5% of allantoin. It is used in ointments for medical and veterinary use in wounds and ulcers to stimulate growth of healthy tissue, and also in hand lotions, creams, lipsticks, pomades, after-shave lotions, and sun-tan preparations for its healing effect.

Allantoin can be determined qualitatively by: (*1*) adding mercuric nitrate to a cooled, saturated, aqueous solution (a white precipitate forms which is soluble in excess mercuric nitrate); or (*2*) boiling a small amount with 10% hydrochloric acid for 3–5 minutes and adding 1% phenylhydrazine hydrochloride solution (when cool, the addition of potassium ferricyanide and hydrochloric acid produces a cherry-red color).

Alloxan (mesoxalylurea, 2,4,5,6(1*H*,3*H*)-pyrimidinetetrone) (IV), $C_4H_2N_2O_4$, formula weight 142.07, exists as colorless to pink crystals easily soluble in water and in alcohol, slightly soluble in chloroform and in petroleum ether, and insoluble in ether. It is prepared by oxidizing uric acid with concentrated nitric acid or chlorine in the cold (see p. 482), by treating alloxantin (VI) with fuming nitric acid (7), or by oxidizing barbituric acid with chromic acid (9). Alloxan monohydrate is available commercially for use in nutrition experiments and in organic syntheses, as of riboflavin (*q.v.*).

Alloxantin (uroxin) (VI) forms a dihydrate (IX), $C_8H_6N_4O_8.2H_2O$, formula weight 322.19, a white crystalline powder, which on exposure to air takes up ammonia, turning red. It is very soluble in hot water and slightly soluble in cold water, cold alcohol, and ether. It is prepared by oxidation of uric acid with potassium chlorate followed by reduction with hydrogen sulfide (14). It is commercially available and is used in the synthesis of riboflavin.



(IX) alloxantin dihydrate

Parabanic acid (imidazolidinetrione, oxalylurea) (III), $C_3H_2N_2O_3$, formula weight 114.06, is a white crystalline powder, m.p. 243°C. (decompn.). It is soluble in 20 parts cold water and in alcohol. It is prepared by the oxidation of uric acid with 30% hydrogen peroxide (3), by the oxidation of alloxan, or by treating hydantoin with bromine and water.

Bibliography

(1) Beilstein, 4th ed., Vol. XXVI, p. 513; 1st Suppl. Vols. XXVI-XXVII, p. 151; 2nd Suppl. Vol. XXVI, p. 293.
(2) Benedict, S. R., and Francke, E., *J. Biol. Chem.*, **52**, 387 (1922).
(3) Blitz, H., and Schiemann, G., *Ber.*, **59**, 721 (1926).
(4) Cavalieri, L. F., Blair, E. V., and Brown, B. G., *J. Am. Chem. Soc.*, **70**, 1240 (1948).
(5) Fischer, E. G., Neumann, W. P., and Roch, J., *Chem. Ber.*, **85**, 752 (1952).
(6) Hartman, W. W., Moffett, E. W., and Dickey, J. B., in Blatt, *Organic Syntheses*, Wiley, N.Y., 1944, Collective Vol. II, p. 21.
(7) Hartman, W. W., and Sheppard, O. E., in Smith, *Organic Syntheses*, Wiley, N.Y., 1943, Vol. 23, p. 3.
(8) Hawk, P. B., Oser, B. L., and Summerson, W., *Practical Physiological Chemistry*, 12th ed., Blakiston, N.Y., 1947, p. 730.
(9) Holmgren, A. V., and Wenner, W., in Arnold, *Organic Syntheses*, Wiley, N.Y., 1952, Vol. 32, p. 6
(10) Lavagne-Mézière, *Ann. biol. clin. (Paris)*, **9**, 340 (1951).
(11) Levene, P. A., and Bass, L. W., *Nucleic Acids*, Chem. Cat. Co., Monograph 56, 1931.
(12) McElvain, S. M., *J. Am. Chem. Soc.*, **57**, 1303 (1935).
(13) Mathews, A. P., *Physiological Chemistry*, 5th ed., Wood, N.Y., 1930.
(14) Nightingale, D., in Smith, *Organic Syntheses*, Wiley, N.Y., 1943, Vol. 23, p. 6.
(15) *Thorpe's Dictionary of Applied Chemistry*, 4th ed., 1954, Vol. XI, p. 802.
(16) Tilden, Doris H., *J. Assoc. Offic. Agr. Chemists*, **34**, 498 (1951).
(17) U.S. Pat. 2,302,204 (1942), H. S. Gable and J. M. Bloodsworth.
(18) Ger. Pat. 864,870 (Jan. 29, 1953) (cl. 12*p*, 7_{10}), H. Bredereck and H. G. von Schuh.

S. B. Mecca

URIDINEDIPHOSPHOGLUCOSE, $C_{15}H_{24}N_2O_{16}P_2$. See *Sugars (commercial)*, Vol. **13,** p. 248.

URIDYLIC ACID, $C_9H_{13}N_2O_9P$; **URIDINE,** $C_9H_{12}N_2O_6$. See *Nucleic acids*, Vol. **9,** pp. 509, 510.

URONIC ACIDS; URONIDES. See *Glycosides*, Vol. **7,** p. 263; *Gums*, Vol. **7,** p. 329; *Pectic substances*, Vol. **9,** p. 903; *Sugars (derivatives)*, Vol. **13,** p. 265.

URSOLIC ACID, $C_{30}H_{48}O_3$. See *Terpenes (tri-)*, Vol. **13,** p. 767.

USTIN, $C_{19}H_{16}ClO_5$. See *Antibiotics*, Vol. **2,** pp. 29, 35.

UVAROVITE, $Ca_3Cr_2(SiO_4)_3$. See *Silica and silicates (mineral)*, Vol. **12,** p. 279.

V

VACCENIC ACID, $CH_3(CH_2)_5CH{:}CH(CH_2)_9COOH$. See *Fatty acids*, Vol. **6**, pp. 175, 271.

VACCINES

See also *Microorganisms*; "Biologicals" under *Pharmaceuticals*; *Serums and serology*.

A vaccine is a biological preparation administered as a prophylactic measure to actively immunize humans and animals against a variety of infectious agents. (For differentiating between *active* and *passive* immunization, see Vol. **12**, p. 182.) In a stricter sense, a vaccine refers to a preparation consisting of a living, nonvirulent (attenuated) viral disease agent. Through common use, the term erroneously refers to any biological preparation administered orally or parenterally for therapeutic, prophylactic, or diagnostic purposes.

The purpose of administering a vaccine is to stimulate the production of specific antibodies in an individual in some harmless manner, so that upon being subsequently exposed to the infectious agent the individual will either not contract the disease or experience it in a mild, modified form only.

The terms vaccine (Latin *vacca*, cow) and vaccinate were introduced in 1796–1798 by Jenner while conducting his classical experiment of successfully immunizing a human subject against smallpox by means of a cowpox virus (vaccinia) of low virulence. Nearly a century after Jenner's work, Pasteur adopted the terms vaccine and vaccinate while conducting his immunization experiments with chicken cholera, anthrax, and rabies; these experiments resulted in his understanding of the broadly applicable principles of the science of immunization not previously realized by Jenner and his colleagues.

For many centuries it had been realized that if an individual became ill as a result of one of many varieties of "contagion" and survived, he rarely, if ever, again became ill with a disease that exhibited the same symptoms and characteristics. Indeed, the practice of intentionally communicating a mild form of smallpox to prevent contracting a more virulent form was not uncommon among various Oriental races. Such human "variolation" was conducted by ingesting or inhaling dried crusts containing the smallpox virus (*variola*; L. *varius*, various), as well as by inoculating pock fluid through the skin, the material being obtained from individuals suffering from mild infections only. The latter procedure was introduced into Europe about 1717 and notes concerning the scarification procedure appeared in published form as early as 1763 (1,30). This scarification procedure, however, usually left pock marks on the patient's face, and sometimes resulted in communicating a severe or fatal rather than a mild form of the disease.

Factors Influencing Immunization. Among the various aggressive defense mechanisms that enable an individual to acquire a certain degree of resistance (or insusceptibility) to the invasion of infectious or toxic agents is the appearance of specific antibodies (circulating) in the blood stream. In a great number of infectious dis-

cases, it has been possible to correlate the development of a satisfactory state of acquired immunity (resistance) with the development of demonstrable, specific antibodies. This does not mean that all antibodies are necessarily beneficial or protective (allergens, for instance). Nor does it mean that antibodies are demonstrable in all infectious diseases or in all instances of any particular infectious disease—from which it is possible to speculate that either such antibodies do not exist or the method for demonstrating them is not adequate. (See *Allergy*; *Serums and serology*; as well as the discussions of Boyd (37), McMaster (21), Freund (9), and Edsall (5).) Nevertheless, the close association of antibodies with the immune state induced investigators, as long as fifty years ago, to attempt the artificial production of measurable antibodies in both humans and animals by means of inoculations of harmless vaccines. In certain instances such preparations were unsuccessful, but in others the almost dramatic reduction of the prevalence of numerous infectious diseases has been of historical importance.

Unfortunately, there is no single method by which such immunizing preparations can be produced. The individual manufacturing procedure of each vaccine depends, to a great degree, on the manner in which the infective (or toxic) agent is propagated or elaborated. Certain of these variations will be noted later during the discussion of vaccine production methods (see p. 492).

Since the purpose of administering a vaccine is to produce antibodies, it is well to point out the rather large number of unrelated (yet somewhat dependent) factors that affect the antibody response, so that it may be realized that certain vaccines confer immunity and others do not; that certain individuals can be immunized and others cannot; that one vaccine confers a long-lasting immunity and another does not, etc. The factors that attend all such situations are not always explainable. In some instances, it has not been possible to correlate the laboratory-measured antigenicity of a vaccine with the antigenic property that protects (or fails to protect) the vaccinated animal against a fully virulent dose of the infective agent.

In considering the various factors that affect the antibody response, it is necessary to realize that any or all may vary, and that it is difficult to evaluate one without assuming that the others remain more or less constant. It is also necessary to assume that the antigenic preparation is nonliving and that, unless otherwise indicated, a single (primary) inoculation is involved. The assumption must be made, too, that the method of detecting antibody response is both constant and adequate. Edsall (5) has outlined these factors as follows:

The **pattern of response**, which is considered as consisting of three phases or periods. (*a*) The *latent period*, which begins immediately upon the introduction of the antigen and extends until the initial appearance of detectable antibodies; a period during which no antibodies appear; (*b*) the *period of antibody increase* during which the detectable antibodies rise rapidly to a sharp peak or a more persistent plateau; (*c*) the *period of antibody decrease* wherein the detectable antibody titer falls but at a slower rate than in the rising phase. Detectable antibodies have been measurable for months as well as years and, in some instances, have persisted for a lifetime. Such factors that may contribute to the decrease of antibodies are: their actual destruction by the defense mechanism of the host; the unstable nature of the antibody; and the excretion of the antibody by some means not in use ordinarily.

The **effective dose** of the antigen, that is, the amount required to produce maximum antibody response, above which further increases of dosage yield proportionately less antibody response.

The **chemical state** of the antigen, which concerns the degree of chemical purity of the prepara-

tion, since the immune response is directed toward all antigenic components of a vaccine preparation regardless of whether the provoked antibody is beneficial or harmful to the vaccinated individual.

The **physical state** of the antigen, which governs the rate of absorption and persistence of the dose. A slow rate of absorption, in general, increases the antibody titer as well as prolongs its existence. From a practical standpoint, it has been possible to incorporate such desirable features into certain vaccines by the addition of various so-called *adjuvants*, such as mineral oil, alum (aluminum potassium sulfate), aluminum hydroxide, aluminum phosphate, lanolin preparations or polyvinylpyrollidone (PVP), to slow down absorption of the vaccine.

The **route of administration**, the effect of which, for the most part, must be determined experimentally. It is difficult to compare the advantage of one injection route over another because, usually, each route will involve a different volume of antigen. For instance, an intradermal dose is much less than the one tolerated subcutaneously or intramuscularly. Animal experimentation has demonstrated that, in general, a particulate antigen is more effective if given by the intravenous route; a soluble antigen, by the subcutaneous route.

When the vaccination involves more than one injection, the **interval between doses** as well as the matter of the secondary response must be considered. (See the discussions by Freund (9).) It has been proved that a second inoculation of a vaccine, if given after a suitable period of time from the first inoculation, will result in a shorter latent period and a higher antibody peak as well as in a slower rate of antibody decrease. (In more practical terminology, this is known as the "booster shot.") A third injection, if properly spaced, will also provide, for the most part, a more solid immunity. Thus, in the case of nonliving vaccines, a higher and more persistent degree of immunity can be achieved by the proper spacing of several inoculations over that offered by a single dose. The volumes, the route, and the interval as well as the number of injections must be determined experimentally.

From the practical aspect, the multiple-injection method of vaccination has several disadvantages: certain individuals may become sensitized so that subsequent injections may prove more damaging than beneficial; a certain number of individuals will not be adequately immunized by failing to receive the full course of injections and thus become a hazard to unsuspecting groups of individuals; multiple vaccinations are more expensive.

Host Factors. Experiments have demonstrated that certain species, as well as certain individuals within the species, vary in the ability to resist infection as well as in the capacity to form antibodies upon vaccination. At one time it was considered that infants were incapable of good antibody production. This opinion has been altered by the numerous instances of infants (three months or less) that have developed satisfactory degrees of immunity following vaccination against diphtheria, pertussis (whooping cough), and tetanus.

The theory that **host injuries** serve as factors which may alter the antibody response has not been conclusively proved. Such considerations must be noted, however, until justified or denied. Some of these possible factors are: dietary deficiencies; protein deficiencies; heat, cold, or other alterations of physical environment; the influence of hormones; and the influence of x-rays.

A satisfactory vaccine does not always contain the infectious agent per se. For instance, a satisfactory vaccine for diphtheria has not yet been prepared by the use of the *Corynebacterium diphtheriae* bacterial cell body alone. However, these bacteria produce a powerful "soluble" (nonparticulate) toxin (exotoxin) which is responsible for most, if not all, of the characteristic features of the disease. Exotoxins are highly antigenic, and it is possible to induce a state of active immunity by the use of a vaccine containing a modified (nontoxic) form of the toxin called the *toxoid* (see Vol. **10,** p. 245).

In other instances, such as typhoid fever, which is caused by *Salmonella typhi*, toxins also play a characteristic role during the course of the disease. These toxins, however, are endotoxins and are only weakly antigenic. Satisfactory immunity is produced by the use of the bacterial cell bodies of (usually) several species: *S. paratyphi A* and *S. paratyphi B* in combination with *S. typhi*. In still other instances, a suitable vaccine may contain the infective agent per se along with a soluble antigenic

component as in the preparations used for immunizing against Rocky Mountain spotted fever and epidemic typhus.

General Characteristics and Qualifications

The desirable qualities of any successful vaccine are (18): (*a*) the vaccine should be safe for administration. It should not be virulent and should not produce anything more than a minimum local or systemic reaction. (*b*) the vaccine should be capable of producing an immunity against a wide variety of the different types (species) of a particular infectious agent; (*c*) a vaccine should provide an adequate immunity by means of only a few inoculations; (*d*) the immunity so produced should be durable; (*e*) it should be possible to prepare the vaccine on a mass-production basis; (*f*) the vaccine should be inexpensive.

The various preparations that can be used to obtain satisfactory immunization are (14):

Living, Fully Virulent, Disease-Producing Agents. The administration of such preparations will, in all probability, produce the disease and afford an immunity identical to that produced by accidently contracting and experiencing the infection. The immunization of humans is rarely attempted by the use of vaccines of this type. In experimental work with animals, however, such procedures are often used. It is possible, in certain cases, to modify the effect of the virulent agent in various ways: (*1*) administering such a preparation after a certain amount of immunity has been previously established by the use of other varieties of vaccines or nontoxic substances; (*2*) using such a vaccine in conjunction with a specific antiserum (a procedure often used for immunizing swine against hog cholera); (*3*) administering sublethal doses of such a vaccine and gradually increasing the dosage as effective immunity develops; (*4*) administering a vaccine of this type by a route that may be unfavorable for producing the fully developed infection.

Living Infectious Agents Whose Virulence Has Been Reduced (Attenuated). At least three different situations exist that have permitted the preparation of vaccines of this type: (*1*) It is possible to produce an attenuated form of certain bacterial and viral agents by propagating the agent in an unfavorable environment or in a host other than that in which the disease normally occurs. The virulence of several bacteria (*Escherichia coli* and various species of *Salmonella*) can be reduced by culturing the organisms at an unusually high temperature or in the presence of specific immune serum. Pasteur converted the virulent "street" form of the dog rabies virus into the modified "fixed" form by serially passing the virus in rabbits. The virulent form of the yellow fever virus was rendered avirulent by being propagated in tissue culture (19). The close immunologic relationship between the variola (smallpox) and vaccinia (cowpox) viruses (see p. 488, refs. 12,13,28) permits the use of the vaccinia virus (virulent in cattle, avirulent in man) for conferring immunity against the variola virus (virulent in man). (*3*) Occasionally, an agent is isolated, in nature, that is capable of producing immunity without demonstrating the property of virulence. A particular strain (Iowa) of rickettsia exists which exhibits no evidence of virulence in laboratory animals but will protect such animals against a fully virulent form of the agent of Rocky Mountain spotted fever (2).

Killed Infectious Agents. Such preparations immunize without producing the disease in any form. Vaccines of this type, such as typhoid, pertussis, and cholera

vaccines, etc., are useful against agents that produce no soluble toxin. The living agents may be killed by means of heat, treatment with chemicals, or by means of ultraviolet irradiation.

Antigenic Fractions or Products of Infectious Agents. Vaccines of this type consist of toxins, toxoids, partially autolyzed cells (pneumococci), or protective antigenic fractions produced by physical treatment (*Hemophilus pertussis* (24,25)).

A Mixture of Immunizing Substances. Such a vaccine may consist of: (*1*) A toxin and an antitoxin; (*2*) a combination of one or more toxoids in conjunction with a suspension of bacteria (such as one containing diphtheria and tetanus toxoids and the whooping cough bacillus (*Hemophilus pertussis*)); (*3*) several species of one genus of bacteria (typhoid-paratyphoid, see p. 494) or of viruses (influenza vaccines usually consist of one or more strains of Type A prime, one of Type A and one of Type B); or (*4*) one or more species of bacteria of several genera such as one containing suspensions of *Micrococcus catarrhalis, H. influenzae, Bacillus friedlanderi,* and several species of streptococci, staphylococci, and pneumococci.

Antigenic Substances Not Related to the Particular Infection Involved. Although foreign protein therapy is not popular at the present time and such preparations are not considered vaccines for active immunization as defined at the beginning of this article, the previous wide use of preparations of this type warrants a brief discussion. The therapeutic (not prophylactic) value of the parenteral use of such preparations as milk, normal blood serum, peptone, bacterial vaccines (typhoid), as well as a mixture of proteins obtained from nonpathogenic bacteria, is to produce a nonspecific systemic reaction characterized by shock, fever, vascular dilatation, and certain blood cellular activity. Such vaccines were once extensively used in conditions such as pneumonia, puerperal sepsis, arthritis, various nervous diseases (multiple sclerosis, peptic ulcer), and certain ocular diseases (29).

Vaccine Production Methods

There are various methods of preparing vaccines suitable for immunizing against a variety of infectious agents, which include bacteria, rickettsiae, and viruses. Vaccines produced by means of standard laboratory-maintained agents are called *stock vaccines,* while those prepared by means of the patients' own particular infectious agent are called *autogenous vaccines.* The selected method, in most instances, depends upon the properties or characteristics of the disease-producing agent. In general, the following problems must be met: (*1*) selecting a particular strain (species or type) of the agent; (*2*) propagating the agent under known controllable conditions; (*3*) separating the desired antigenic substances from those neither desired nor required; (*4*) reducing or destroying virulence (or toxicity) without reducing or destroying the antigenic properties of the components; and (*5*) preserving the final product so that its immunizing capacity will be retained for a satisfactory period of time under optimum storage conditions.

So-called "preserving agents" may be added to vaccines, but they are preservative only in the sense that such compounds insure against bacterial (or other) contamination and will thus prevent the destruction of the product by such means. These compounds do not prevent the gradual degradation of the protein constituents with the attendant loss of antigenicity. "Killing agents" and "preserving agents" are usually, chemically, the same compounds, for example, formaldehyde, phenol, tricresol, sodium (ethylmercuri)thiosalicylate (thimerosal), and phenylmercuric borate.

All licensed vaccines (see p. 501) produced for market distribution must conform to the standards, if such exist, as outlined by the National Institutes of Health of the Federal Security Agency (for human products) or the Animal Inspection and Quarantine Branch (formerly Bureau of Animal Industry) of the Department of Agriculture (for animal products).

BACTERIAL VACCINES

The present discussion includes only those vaccine preparations containing the bacterial cell body per se; for the production of vaccines containing soluble constituents of bacteria (toxins), see *Serums and serology*, Vol. **12,** p. 184. The efficacy of a vaccine depends upon the antigenicity of the infectious agent and not necessarily upon whether the bacteria can be grown in the laboratory on artificial or semisynthetic media. Certain bacteria, such as the typhoid and related organisms, are "good" antigens while the gonococcus, for instance, is a "poor" antigen (27). Furthermore, a vaccine that is capable of producing an adequate immunity in one individual may not produce the same degree of immunity in another individual.

Even after it has been established that it is possible to produce a satisfactory degree of immunization by means of a certain bacterial vaccine, the matter of selecting and maintaining a particular bacterial strain suitable for vaccine production remains. After a suitable strain has been selected, it is usually preserved by vacuum drying. In certain cases, the property of virulence may be associated with desirable antigenic features, necessitating the maintenance of a virulent stock culture. In other instances, certain antigenic structures vary with the cultural morphology of a strain (or variant), for example, the antigenic structure of a rough, nonmotile variant of *Salmonella typhi* is not the same as that possessed by a smooth, motile form. After the desirable antigenic properties of a strain have been ascertained, the strain is checked at frequent intervals to insure that these qualities have not been lost. Serial passages through animals often restore virulence, while frequent transfers on suitable media will restore smoothness, and propagation on moist media or in broth will restore motility. Undesired antigens, on the other hand, may be eliminated or suppressed by culturing or exposing the bacteria to various immune serums, by culturing under adverse conditions, or by treatment with certain chemicals.

The culture media required for propagating the bacteria may vary from a simple beef infusion agar or broth to a more complicated variety that may require blood serum or whole blood. In any event, the media used should not contain substances antigenic for humans unless it is possible to remove the bacterial growth from the media at some stage during the manufacturing process. Certain ingredients cannot be employed in media for the production of toxoids because of the presence of human blood group A substance. If the organisms are cultured in broth, they may be recovered (and washed, if necessary) by centrifuging or filtering. If grown on solid media, they may be removed by washing as noted in the example given below.

Except for the production of certain vaccines for use in animals, the organisms must be killed. This may be accomplished by the use of chemicals, heat, or by ultraviolet irradiation. The method must be determined by experience, since a method that may prove satisfactory for one variety of bacteria without destroying antigenicity (or at least provide a minimum of antigen destruction or alteration) may not be suitable for another variety. The killing agent or method of killing must not be such that it will produce harmful effects in humans.

Bacterial vaccines are usually standardized by making counts (see p. 495) of the numbers of organisms, although the potency test (see p. 495) is the actual method of determining the effectiveness of the product.

Typhoid and Paratyphoid Vaccine. This preparation is referred to as a *polyvalent vaccine* since it contains three different bacterial species of the genus *Salmonella* (*S. typhi, S. paratyphi A,* and *S. paratyphi B*). In actual practice, three separate concentrated *stock* (bulk) *vaccines* are prepared; one for each species of *Salmonella*. The *finished vaccine* consists of a diluted mixture of aliquot portions of each stock vaccine. With the exception of the different bacterial species selected and the varying of certain tests that may be required to insure the purity and potency of each species as well as the difference in the numbers of each species contained in the finished vaccine, the various production procedures are essentially the same for each species.

The species of *Salmonella* selected are: *S. typhi* (No. 45-Panama strain No. 58A), *S. paratyphi A* (strain No. 6A, Army Medical Center No. 41-N-22), and *S. paratyphi B* (*S. schottmülleri,* strain No. 10B, Army Medical Center No. 41-H-6).

All stock cultures are preserved in the dried state. The motility, purity, and identity of each organism are frequently checked. At designated intervals, the dried cultures are plated out on a suitable agar medium contained in Petri dishes. Typically smooth colonies are selected and replated. The 4–6 hour growths (at 37°C.) are examined as noted above. The morphology and motility are noted as well as the characteristic physiological and chemical reactions that occur in various fermentable substances. Agglutination tests are also conducted by means of appropriate specific antiserums (see Vol. 12, p. 189).

The seed inoculum is prepared by removing the growth from a 6 × ⅝ in. agar slant by means of 5.0 ml. of broth. The purity is rechecked (Gram stain). The 5.0 ml. quantity of broth is used to inoculate a larger quantity of broth (300 ml.) which is incubated at 37°C. for from 4 to 6 hours. The final culture constitutes the *seed inoculum.*

A large series of bottles (100 or more) containing slants of beef infusion agar are inoculated by introducing a small volume of seed inoculum onto the surface of the agar. After an incubation period of 15–18 hours at 37°C., the growth from each slant is removed in 20–25 ml. of sterile buffered (pH 7.2) physiological salt solution (saline). The suspensions are examined for purity and the organisms are then killed by heating the suspensions at 56°C. for 70 minutes. After cooling, liquid phenol is added to a final concentration of 1.0%. The suspensions are allowed to remain overnight at room temperature. Sterility tests (see p. 495) are made. If satisfactory, the suspensions are filtered through fine-mesh silk, samples are removed for additional tests, another sterility test is conducted on the balance of the stock, and the stock bottles are sealed and stored at 4°C. until needed.

The bacterial growth from 100 bottles of beef infusion agar slants usually yields 2 liters of suspension. The suspensions usually contain 45–60 billion organisms per milliliter in each case.

The finished typhoid and paratyphoid vaccine is prepared by diluting and mixing aliquot portions of the three stock vaccines with buffered saline in such a manner that the final preparation consists of a suspension of 1000 million *S. typhi* organisms per milliliter and 250 million each of *S. paratyphi A* and *S. paratyphi B* per milliliter with a phenol content of 0.5%.

The finished vaccine is examined by means of purity, sterility, and safety tests (see below). A chemical analysis is also made to determine the quantities of salt (NaCl), phenol, and total nitrogen, which must not exceed 0.055 mg./ml.

In addition to these tests, the finished vaccine is examined for potency. Potency test limitations have been established for the *S. typhi* component only; such limitations have not been proposed for the *S. paratyphi A* or the *S. paratyphi B* components, as the uncertainty of killing an animal when either of these components is used makes vaccine evaluation difficult. In actual practice, a potency test is also conducted on the stock *S. typhi* material in order to be certain that the stock can subsequently be used in preparing the finished vaccine and still pass a satisfactory potency test.

The various tests that are conducted on the stock vaccine are as follows (certain of these tests, as well as others, that may be required by the National Institutes of Health (8) are also conducted on the finished vaccine):

Bacterial Counts. This test consists of determining the density of several successive dilutions of the suspension by means of an electric-type colorimeter. By means of the galvanometer readings, the bacterial counts may be computed by the use of a previously prepared specific curve chart. The counts usually fall within the range of 40–60 billion organisms per milliliter.

Safety Tests. Two milliliters of stock vaccine is diluted 1:4 with 0.25% phenol-saline. At least 2 mice are inoculated, subcutaneously, with 1.0 ml. each. The mice are observed over a 10-day period. Both must remain alive and well.

Sterility Test. Aliquot portions of each stock vaccine are aseptically placed in bottles of an appropriate nutrient broth. One series is stored at room temperature and another at 32°C. All containers are observed for 7 days for evidence of bacterial (or other) growth. Contaminated stock vaccines are not used for preparing the finished vaccine.

Identity Test. Aliquot portions of stock vaccine are concentrated to contain 100 billion organisms per milliliter. Each concentrate is examined for identity by conducting a rapid slide agglutination test using specific serums, each containing antibodies to the antigens of *S. typhi, S. paratyphi A*, and *S. paratyphi B*, respectively (see Vol. 12, p. 185).

Purity Test. A small quantity of the material is smeared on glass microscope slides and stained by means of the Gram procedure. All *Salmonella* organisms are Gram-negative. Gram-positive organisms should not be present. This test is a quick preliminary method for picking up Gram-positive organisms. Foreign Gram-negative organisms are picked up later on culture (sterility test).

Potency Test (8) (conducted on stock *S. typhi* and finished vaccine only). This test is a means of comparing the ability of the test vaccine to immunize mice against the immunizing capacity of a standard reference vaccine of known potency. The test consists of determining the survival rates, in comparison with controls, of various groups of mice given successive graded doses of test and reference vaccine (by the intraperitoneal route) and constant doses of a living virulent suspension of *S. typhi* (in 5.0% mucin) inoculated by the same route. The potency of the test vaccine must equal or surpass that of the reference standard. If the number of deaths for the "test" vaccinated mice is not more (for each corresponding dose) than 1 mouse greater than the number of deaths for the "reference" vaccinated mice, the test vaccine is considered equal to the reference vaccine. As a rule, however, test results are not as clearly indicative as this. Then it is necessary to resort to a suitable method of statistical analysis whereby the ED_{50} (the dose effective for 50% of the mice) can be calculated as well as the estimated error (standard error). From these figures, the relative potency of the test vaccine, as compared with the reference vaccine, can be estimated as:

$$\frac{ED_{50}\text{ reference vaccine}}{ED_{50}\text{ test vaccine}}$$

The vaccine is considered satisfactory if the relative potency exceeds 0.6 (60%).

Typhoid and paratyphoid vaccine is usually dispensed in 1.5 ml. (for 1 immunization) and 15 ml. (for 10 immunizations) quantities. The vaccine remains suitable for use for an 18-month period from the date of release under optimum storage conditions.

RICKETTSIAL VACCINES

The rickettsiae, unlike bacterial organisms, require the presence of living cells in order to propagate. This fact complicates the production of rickettsial vaccines in that the matter of separating the rickettsial cell bodies, or their soluble substances, from the living tissues of the host presents, in most instances, a difficult problem. Until it was demonstrated that rickettsiae could be grown in the yolk sac membranes of living chick embryos (3), the organisms were cultivated in the living tissues of various insects, which were, in most cases, the vectors of the disease. A vaccine for Rocky Mountain spotted fever, for example, was prepared from material obtained by artificially infecting ticks (*Dermacentor andersonii*) with *Rickettsia rickettsii* (32). A vaccine for typhus fever was also prepared from lice artificially infected with *R. prowazekii* (Weigl's louse vaccine (35)). In other instances, the infected tissues of various infected laboratory animals (mouse spleen, rat lung) have been utilized in preparing effective rickettsial vaccines. (See refs. 7,10,11,22,26.)

For mass production purposes, a method utilizing rickettsial growth produced in the chick embryonic yolk sac, together with procedures involving the treatment of the material with lipide solvents (4) to remove soluble egg lipides as well as tissue, is far more practical. There are at least two instances, however, in which the above method has not produced a suitable vaccine; *i.e.*, in the case of Q fever (*Coxiella burnetii*) and scrub typhus (*R. tsutsugamushi*). In these instances, it has been considered that failure to effect satisfactory immunization is due to the absence of a "soluble substance" which results, at least in part, from the action of the lipide solvent (7). Reports have been made concerning the use of a living vaccine in the case of scrub typhus (31).

Various rickettsial strains can be maintained in embryonated eggs or in animals. Most strains suitable for vaccine production are highly virulent, and the virulence may be maintained by conducting frequent passages in susceptible laboratory animals.

The purity and identity of the strains can be checked by various *in vitro* tests (complement-fixation—see Vol. **12**, p. 189) and *in vivo* tests. In the latter instance, animals that have survived an intentional infection by receiving sublethal doses of virulent material remain immune to subsequent lethal doses of exceptionally virulent material. Challenging vaccinated animals is also a means of identifying a rickettsial strain.

Certain tests that may be required to check the identity, potency, purity, and safety of a rickettsial vaccine are noted below.

Typhus Vaccine (Epidemic Type). The egg-adapted Breinl strain of *Rickettsia prowazekii* (the causative agent of classical louse-borne (European) epidemic typhus fever) is used in preparing a vaccine for immunizing against this disease. The rickettsiae are maintained both by passage in guinea pigs and in embryonated hen eggs. The virulence of the agent is checked by frequently observing its ability to kill or produce the disease in guinea pigs, to kill embryonated eggs, and to produce a toxic substance in eggs that will kill Swiss white mice. The identity of the agent is continually checked as well as its immunizing capacity, by vaccinating guinea pigs with vaccines produced in other laboratories and subsequently challenging them with the stock strain. The ability of the various vaccines to produce serum antibodies that will specifically neutralize the toxic substance noted above is also observed.

Prior to vaccine production, a *seed inoculum* is prepared from selected infected yolk sac membranes that have been homogenized in a suitable medium (skimmed milk or casein digest solution). This is titrated to determine the optimum dose, which, contained in 0.2 ml., produces maximum growth in yolk sac membranes and kills or produces moribund embryos in 40–50% of the eggs 7 or 8 days after inoculation.

Also, prior to vaccine production, especially selected infected yolk sac membranes are examined for maximum rickettsial growth and for the ability to produce a toxic substance that will kill white mice by intravenous inoculation. The LD_{50} dose of toxic substance (the dose that will kill 50% of a given number of inoculated mice within 24 hours) is determined by titration. The membrane suspension is then diluted so that 4 LD_{50} doses will be contained in 0.5 ml.

Both the suspensions of seed inoculum and toxic substance are preserved at −40° to −50°C. for considerable periods of time—frequently as long as 12 months.

Salmonella-free, 7-day-old embryonated hen's eggs are used for vaccine production. The eggs are candled before inoculation to ensure that the embryo is not dead. A small hole is drilled through the shell of the air sac end of the egg (without penetrating the membranes) with a silicon carbide drill. The area is cleansed with an antiseptic solution and by means of a hypodermic syringe fitted with a 21-gage 1-in. needle, 0.2 ml. of inoculum is aseptically introduced into the yolk sac fluid. The puncture is sealed with a drop of collodion-ether mixture, and all inoculated eggs are placed in an incubator maintained at 34–36°C. at 70% r.h.

On the fourth day after inoculation, the eggs are candled, and all eggs containing dead embryos

are discarded. The eggs are again candled on the fifth and sixth days, and all dead eggs are stored in the cold (5°C.). When 40-50% of the eggs are either dead or moribund, possibly on the seventh or eighth day after inoculation, and microscopic examination of the yolk sac membranes of a few eggs selected at random exhibits suitable rickettsial growth, all eggs are removed from the incubator and stored (usually overnight) in the cold until harvested.

The infected yolk sac membranes are removed from the egg by first dipping the egg in an antiseptic and allowing it to dry partially. The egg is then cracked, and the entire contents are placed on a sterile wire mesh screen. The yolk sac membranes are removed and freed of excess yolk fluid with sterile forceps. The membranes are placed in a suitable container in an ice-water bath.

Convenient quantities of membranes are measured by volume, and a quantity of physiological saline sufficient to make a 15% yolk sac suspension is added. The mixture is homogenized in a Waring Blendor and placed in a separatory funnel or aspirator-type bottle. From ¼ to ½ the volume of ethyl ether is added and the mixture is shaken and allowed to stand overnight in the cold (6-8°C.). The following morning, the bottom (aqueous) layer is removed and stored at 6-8°C. A ½ volume of physiological saline (based on the volume of the original 15% suspension) is added to the yolk sac-ether layer remaining in the funnel. The mixture is shaken and again placed in the cold overnight. The aqueous layer is recovered the following morning and pooled with the aqueous layer previously obtained. The ether is removed from the aqueous layer under reduced pressure.

Formaldehyde is added to 0.05% concentration in solution form. Sodium (ethylmercuri)thiosalicylate is added to make a final concentration of 1:10,000. This preparation constitutes the "bulk" vaccine.

Before its release as a finished vaccine, the bulk preparation must satisfactorily pass certain tests, some of which are also conducted on the finished vaccine (6).

The *sterility* of the vaccine is determined by a similar test to that for bacterial vaccines (see p. 495).

The *potency* of the vaccine is determined by the mouse neutralization test (6). Male guinea pigs are vaccinated, subcutaneously, with 2 doses of vaccine spaced 7 days apart. The animals are bled 14 days after the last injection and aliquot portions of the serums of each animal are pooled. Portions of each of two saline-serum dilutions are separately mixed with equal portions of the toxic yolk sac suspension noted above. The various serum-yolk sac mixtures are held at room temperature for 2 hours. Each mixture is inoculated into separate groups of Swiss white mice and the animals are observed for a period of 24 hours. To satisfactorily pass the potency test, the vaccine must produce a serum which, in a 1:16 dilution or higher, will protect mice for 24 hours against 2 LD_{50} doses of toxic substance.

A *safety test* is performed on the bulk vaccine by inoculating, by the intraperitoneal route, 2 or more healthy guinea pigs (400 g.) with 5.0 ml. each of vaccine. Temperatures are recorded for 12 days. The temperatures should not rise above 39.6°C. after the first 3 days, and all animals must remain normal.

The safety testing of the finished vaccine consists of inoculating, intraperitoneally, 2 or more healthy guinea pigs (300–400 g.) and 2 or more healthy mice (18–20 g.) with 5.0 ml. and 0.5 ml. each of vaccine, respectively. All animals must survive for 7 days without developing any symptoms (weight change, temperature rise, etc.) that can be attributed to the vaccine.

The finished vaccine is also subjected to various other tests that may be required by the National Institutes of Health (6), such as: an identity test, chemical analysis for total nitrogen content, and chemical analysis for determining the quantities of preservatives added (formalin and sodium (ethylmercuri)thiosalicylate).

The finished vaccine is stored at refrigerator temperatures (2–5°C.) and must remain suitable for producing a satisfactory state of active immunity for at least 18 months after the date of release (6).

Typhus vaccine is usually supplied in 1.0 and 20.0 ml. quantities, which are sufficient for 1 and 20 immunizations, respectively.

VIRAL VACCINES

The most effective viral vaccines to date have been those consisting of a living, modified (attenuated) virus incapable of producing the fully virulent disease in the

vaccinated individual. The active immunity produced by the use of attenuated viral vaccines is usually considered to be nearly identical to that produced by actually experiencing the disease. The immunity is extremely effective as well as of long duration. The intentional attenuation of viruses has been achieved, however, in only certain instances: rabies (for cattle and dogs), yellow fever, hog cholera, distemper, Newcastle disease, and a few others. In most cases, the administration of killed viral vaccines has been adopted to ensure the safety of the individual.

The immunity conferred, as a rule, is less effective and of shorter duration than with the attenuated vaccines, although killed viral vaccines have been used successfully against such diseases as: influenza, mumps, rabies (Semple vaccine for human use), various forms of arthropod-borne encephalitis, and other viral diseases of both man and animals. The killing of virus particles either by chemical or physical means usually destroys a portion of its antigenic properties, possibly owing to the fact that the particle possesses more than one antigenic component, one of which is unstable. For instance, the vaccinia virus has several unstable components; at least one of the antigenic components of the psittacosis virus is affected by phenol; the mouse toxin of the Newcastle disease virus is destroyed by freezing (see also ref. 16).

In certain cases, an effective and durable form of immunity can be achieved by the simultaneous administration of a fully virulent virus and a specific, protective antiserum.

Considerable controversy has existed involving the relative merits of a killed or a living viral vaccine for the prevention of poliomyelitis. The situation is complicated in that there are at least three serologically distinct varieties (strains, types) of this virus. The issues under discussion concerned the matter of safety (to the vaccinated individual) as well as the protective ability and the duration of the immunity conferred. At the end of 1954 a large number (approximately one-half million) of children in the U.S. received inoculations of the Salk vaccine, which contained three types of poliomyelitis viruses propagated in monkey kidney tissue culture and subsequently killed by formaldehyde. Announcements made in April 1955 revealed that the vaccine proved to be 80–90% effective with practically no adverse effects. The duration of such protection was still to be evaluated.

If the development of a subclinical infection of poliomyelitis by the administration of a living, attenuated vaccine can be considered analogous to the immunity produced by the attenuated vaccines of smallpox and yellow fever viruses, the results of certain current experiments indicate that it may be possible to produce a vaccine superior to the original killed vaccine. The diminution of the virulence of all three varieties of poliomyelitis virus for monkeys has been accomplished by conducting rapid passages in tissue culture. The fact that two avirulent varieties produce antibodies upon oral administration to human subjects has also been demonstrated. In addition to the encouraging results of these basic studies, the adaption of one variety of the virus to the chick embryo has been accomplished. The latter achievement makes it possible to propagate the virus in a medium not likely to be contaminated with other viruses as well as in a medium readily adaptable to large-scale vaccine production. As yet, however, stable avirulent viruses of the three known types do not exist and not all of the above noted accomplishments have involved these three variant strains. (See references 8a, 17, and 23a for discussions concerning poliomyelitis vaccines. Also, published reports were not yet available in April, 1955, concerning the proceedings of

the Third International Poliomyelitis Conference (Rome, 1954) nor of the Conference on Biology of Poliomyelitis (New York, January 20 and 21, 1955)).

Because of the various particular properties of viruses, the matter of preparing effective vaccines presents many problems. The size of virus particles is such that they do not readily lend themselves to concentration and purification procedures applicable to other infectious agents. The size may vary from 450 mμ for the psittacosis virus (visible by means of the ordinary light microscope) to 240 mμ for vaccinia, 115 mμ for influenza, 25 mμ for poliomyelitis, and 10 mμ for the virus of hoof and mouth disease, as compared with the size of the typhoid bacillus, which varies from 1.0 to 3.0 by 0.5 μ.

The fact that viruses propagate only in living cells also complicates the matter of vaccine production. Certain viruses, such as influenza, mumps, and Newcastle, can be cultivated on living membranes and in the relatively clear fluid of the chick embryo. The collection of the chorioallantoic membranes and fluid is an easy matter and to separate (and concentrate) the virus from such material involves relatively simple procedures. Other viruses, however, propagate only in such dense tissues as the brain or spinal cord, spleen, and blood, and the separation of the virus from such material is extremely difficult or impossible without completely destroying the effective antigenicity of the virus.

When membrane or chick embryo fluid is used, the finished vaccine contains very little host tissue, and the proportion of virus to tissue is large; while with brain or spinal cord, etc., the finished vaccine contains a great deal of host tissue and the proportion of virus to tissue is extremely minute. The presence of such tissue is a continual hazard to the vaccinated individual, due to the fact that since the proportionate virus content is small, several inoculations of the vaccine may be required to produce an effective immunity. The individual thus also develops antibodies to the tissue stimulus, which may result in an allergic response of some seriousness. The Pasteur treatment of rabies, which consists in administering numerous doses of rabbit neural tissue (in which the virus has become avirulent) results, in certain instances, in post-vaccinal paralysis. Horses that have received a vaccine (containing horse tissue) for virus abortion and swine that have received a vaccine (containing swine tissue) for hog cholera have been known to develop antibodies that have resulted in the deaths of their newborn (20) in a manner analogous to that of an Rh-sensitized mother whose newborn presents evidence of erythroblastosis fetalis. A highly desirable feature of vaccines containing large quantities of tissue is that an effective immunity is produced that will persist for many years.

Hog Cholera Vaccine. The method described involves the production of a vaccine suitable for immunizing swine against the infectious viral agent of hog cholera by means of a live virus that has been modified (attenuated) by continued propagation in rabbits (15,16,36).

The rabbit-adapted strain of hog cholera virus is maintained in the living state by continually inoculating rabbits intravenously with 2.0 ml. of 10% (by volume) infected minced-rabbit tissue or whole defibrinated blood from infected rabbits. Such passages are made every 3–5 days. Stock virus is also kept by freezing and drying (under high vacuum) infected rabbit tissue or blood.

The purity of the virus is frequently checked by inoculating susceptible swine and challenging them after 7 to 21 days with a virulent, living strain of hog cholera virus. The survival of the challenged animals confirms the identity of the immunizing agent. The bacterial sterility of all virus-containing material is continually checked by inoculating a suitable culture medium with aliquot

portions of infected blood or tissue. Observations of the media, both at room temperature and at 37°C., are made for a 48-hour period.

Healthy rabbits, 8–9 lb. in weight, of either sex are used for vaccine production. The animals are inoculated intravenously with 2.0 ml. of infected tissue or blood (see above). After 3–5 days, the rabbits are exsanguinated by cardiac puncture while under anesthesia. The blood is collected in a closed receptacle (kept in an ice water bath) containing an anticoagulant solution. Since the virus is pantropic (found in various organs and tissues), the heart, spleen, liver and kidneys are also aseptically removed from each rabbit. These organs are weighed, minced, and mixed with a sufficient quantity of sterile saline containing a stabilizing agent such as casein hydrolyzate (N-Z-Amine B) to make a 30.0% tissue suspension by weight. Blood and tissue suspension are then combined in aliquot proportions and mixed with a quantity of 5.0% sodium citrate solution sufficient to make a 12.0% suspension based on the combined weights of blood and tissue. The final suspension is homogenized in an Eppenbach mill.

The material is successively passed through sterile gauze and bolting silk and remixed to insure a homogeneous suspension. Samples are removed for bacterial sterility testing. A preserving agent is not added. The balance of the suspension is aseptically dispensed into suitable vials of convenient size. The contents are vacuum-dried, and the vials are sealed under high vacuum.

For vaccination and testing purposes, the dried contents of the vial are reconstituted to the original volume with water.

Reconstituted vials are checked for bacterial sterility (see p. 499) safety, and potency.

Safety Test. Eight mice (18–22 g.) are inoculated, subcutaneously, with 1.0 ml. of reconstituted vaccine and observed for a period of 7 days. At least 7 mice must survive this period without showing symptoms that can be attributed to pathogenic bacteria present in the vaccine.

Potency Test. At least 14 swine (40–115 lb.) are required for this test; 10 for immunization and 4 for controls. The control swine are kept in pens well separated from the immunized group. Swine are immunized by means of injecting 2.0 ml. of the reconstituted vaccine into the inner thigh muscles. After a 7 day period, all swine, including the controls, receive an intramuscular injection of 2.0 ml. of hog cholera virus fully virulent for swine.

To pass a satisfactory potency test, at least 3 of the control swine must be visibly sick on the third day after inoculation, develop grave symptoms, and, if killed or found dead, exhibit typical lesions; while at least 9 vaccinated swine must remain alive and well throughout this period.

Additional testings of the finished vaccine may also be required, such as may be designated by the Animal Inspection and Quarantine Branch of the United States Department of Agriculture.

This vaccine is usually dispensed in quantities sufficient for 5, 10, 25, or 50 immunizations and, in the dried form, is potent for at least 1 year if stored at refrigerator temperatures. The active immunity induced by means of this vaccine remains for 2 years or more.

CUTANEOUS IMMUNITY TEST AGENTS

Although the preparations noted here are administered in a parenteral manner (subcutaneously), they are used to determine the state of immunity or susceptibility (diagnosis) rather than to produce active immunity (prophylaxis).

Individuals who have been exposed to, or suffer from, tuberculosis, lymphogranuloma inguinale, Ducrey's disease (chancroid), trichinosis, mumps, and various other diseases become hypersensitive to certain antigenic components of the infecting agent. If such individuals receive an inoculation of a preparation consisting of the respective antigenic substances, they usually exhibit an allergic response as evidenced by the development of a characteristic erythematous or indurated area (wheal) at the site of the injection. This is called a "positive skin test."

The interpretation of such a test varies with the particular disease involved in that a state of immunity is indicated, but it does not indicate whether or not the infection is either recent or active.

In determining individual susceptibility to scarlet fever or diphtheria, the skin

test involves a somewhat different situation. Preparations consisting of the toxic principles of the *Streptococcus pyogenes* or *Corynebacterium diphtheriae* organisms produce, in normal individuals, a characteristic wheal at the site of injection. If the individual, however, possesses circulating antibodies to either of these toxins, the toxic substance will be neutralized and the skin reaction will not appear. Thus, if the test is *positive*, the individual is susceptible since detectable antibodies are not present with which to combat infection; if the test is *negative*, the individual is immune since detectable antibodies are present which, if of adequate strength, will prevent infection.

Such skin test procedures are known by a variety of names, such as: the Dick test (scarlet fever); the Schick test (diphtheria); the Frei test (lymphogranuloma inguinale); the Ito-Reenstierna reaction (chancroid); the von Pirquet reaction (administration of tuberculin by means of the scarification procedure); the Mantoux test (intradermal method of administering graded, measured quantities of tuberculin).

See also *Allergens*.

Recognized Preparation and Licensed Vaccines

Vaccine preparations for humans that are recognized by U.S.P. XIV, N.F. IX and N.N.R. are: **Bacterial vaccines:** cholera, N.F., N.N.R. 1952; pertussis (also alum precipitated), U.S.P., (also alum precipitated; aluminum hydroxide adsorbed), N.N.R. 1954; plague, N.F.; typhoid, U.S.P.; typhoid-paratyphoid, U.S.P.; undulant fever, N.N.R. 1953. **Rickettsial vaccines:** Rocky Mountain spotted fever, N.N.R. 1952; typhus (epidemic), U.S.P. **Viral vaccines:** influenza (polyvalent), N.N.R. 1954; rabies, U.S.P.; small pox, U.S.P.; yellow fever, U.S.P. **Mixed vaccines:** diphtheria toxoid and pertussis combined, U.S.P., (also alum precipitated; aluminum hydroxide adsorbed), N.N.R. 1954; diphtheria and tetanus toxoids and pertussis combined (also alum precipitated; aluminum hydroxide adsorbed), N.N.R. 1954. **Cutaneous immunity test agents:** diphtheria toxin (Schick test), U.S.P.; Scarlet fever toxin (Dick test), N.F.; Tuberculin (old), U.S.P., (purified protein derivative of tuberculin (P.P.D.)), U.S.P., N.N.R. 1954.

Various manufacturing concerns have been licensed (34) to prepare and market the following vaccines (vaccines prepared with "No U.S. Standard of Potency" are not included): **Bacterial vaccines:** cholera, pertussis (alum precipitated), pertussis (fluid), plague, typhoid, typhoid-paratyphoid. **Rickettsial vaccines:** Rocky Mountain spotted fever, typhus (epidemic), typhus (murine). **Viral vaccines:** influenza, encephalitis (herpes "F" strain), equine encephalomyelitis (eastern), equine encephalomyelitis (western), mumps, rabies, smallpox. **Mixed vaccines:** diphtheria toxoid and pertussis combined, diphtheria and tetanus toxoids and pertussis combined. **Cutaneous immunity test agents:** diphtheria toxin (Schick test), lymphogranuloma venereum, mumps and histoplasmin, scarlet fever toxin (Dick test), tuberculin: autolytic (old), P.P.D., patch test.

Various veterinary vaccines that have been produced by license (33) are: **Bacterins** (bacterial vaccines): anthrax, avisepticus-gallinarum, blackleg, blackleg-hemorrhagic-septicemia, bronchisepticus-coli-pasteurella, bronchisepticus-streptococcus, bronchisepticus-streptococcus-typhimurium, clostridium chauvei-septicus, clostridium chauvei-septicus pasteurella, clostridium hemolyticum, clostridium-novyi, clostridium perfringens Type D, coli-enteritidis, coli-enteritidis-pasteurella, coli-staphylococcus-streptococcus, colon-bacillus, corynebacterium-pasteurella gallinarum-

typhimurium, hemorrhagic-septicemia, pasteurella avicida, pasteurella-salmonella-choleraesuis, pseudomonas-staphylococcus, salmonella-abortivoequina, salmonella-choleraesuis, salmonella-typhimurium, staphylococcus-streptococcus, streptococcus. **Vaccines and viruses:** anthrax (spore), blackleg (tissue), brucella abortus, canine-distemper, canine-distemper vaccine in bronchisepticus-streptococcus-typhimurium bacterin, canine-distemper virus, distemper-fox, distemper-mink, encephalomyelitis (eastern) (western) (eastern and western), erysipelothrix rhusiopathiae, feline-distemper, fowl-laryngotracheitis, fowl pox, hog cholera (vaccine), hog cholera (virus), infectious canine hepatitis, Newcastle disease, ovine-ecthyma, pigeon pox, rabies, wart. **Mixed bacterins:** avian, bovine, canine, chinchilla, equine, feline, lepine, ovine, porcine.

Bibliography

(1) Blaxall, F. R., *A System of Bacteriology*, His Majesty's Stationery Office, London, 1930, Vol. VII, ch. 7.
(2) Cox, H. R., personal communication.
(3) Cox, H. R., *Pub. Health Rept.*, **53**, 2241 (1938).
(4) Craige, J., *Can. J. Research*, **E23**, 104 (1945).
(5) Edsall, G., in Papenheimer, A. A. (ed.), *The Nature and Significance of the Antibody Response*, Columbia Univ. Press, N.Y., 1953, pp. 69–89.
(6) Federal Security Agency, National Institutes of Health, *Minimum Requirements: Epidemic Typhus Vaccine*, 5th rev., Feb. 4, 1953.
(7) Federal Security Agency, National Institutes of Health, *Studies of Typhus Fever* (Bull. No 183), 1945.
(8) Federal Security Agency, National Institutes of Health, *Minimum Requirements: Typhoid and Paratyphoid Vaccine*, 2nd rev., Dec. 8, 1953.
(8a) Fox, J. P., *J. Louisiana State Med. Soc.*, **105**, 235–244 (1953).
(9) Freund, J., in Papenheimer, A. A. (ed.), *The Nature and Significance of the Antibody Response*, Columbia Univ. Press, N.Y., 1953, pp. 46–68.
(10) Fulton, F., and Joyner, L., *Lancet*, **2**, 729 (1945).
(11) Henderson-Begg, A., and Fulton, F., *J. Pathol. Bacteriol.*, **58**, 381 (1946).
(12) Horgan, E. S., *J. Hyg.*, **38**, 702 (1938).
(13) Horgan, E., and Mansour, A. H., *J. Hyg.*, **39**, 615 (1939).
(14) Jordan, E. O., and Burrows, W., *Textbook of Bacteriology*, 14th ed., Saunders, Philadelphia, 1945.
(15) Koprowski, H., James, T. R., and Cox, H. R., *Proc. Soc. Exptl. Biol. Med.*, **63**, 178 (1946).
(16) Koprowski, H., James, T. R., and Cox, H. R., *Proc. U.S. Livestock Sanitary Assoc.*, Fifty-Fifth Annual Meeting, 1951.
(17) *Lancet*, **267**, 851 (1954).
(18) Leavell, H. R., and Clark, E. G., *Textbook of Preventive Medicine*, McGraw-Hill, N.Y., 1953.
(19) Lloyd, W., Theiler, W., and Ricci, N. I., *Trans. Roy. Soc. Trop. Med. Hyg.*, **29**, 481 (1936).
(20) Markham, F. S., *J. Iowa State Med. Soc.*, **44**, 505 (1954).
(21) McMaster, P. D., in Papenheimer, A. A. (ed.), *The Nature and Significance of the Antibody Response*, Columbia Univ. Press, N.Y., 1953, pp. 13–45.
(22) Moulton, F. R. (ed.), *Rickettsial Diseases of Man*, Am. Assoc. Advancement of Science, Washington, D.C.
(23) Papenheimer, Jr., A. A. (ed.), *The Nature and Significance of the Antibody Response*, Columbia Univ. Press, N.Y., 1953.
(23a) Paul, J. R., *Connecticut State Med. J.*, **18**, 140–144 (1954).
(24) Pillemer L., *Proc. Soc. Exptl. Biol. Med.*, **75**, 704 (1950).
(25) Pillemer, L., Blum, L., and Lepow, I. H., *Lancet*, **1954, II**, 1257.
(26) Pinkerton, H., *Bacteriol. Revs.*, **6**, 37 (1942).
(27) Raffel, S., *Immunity, Hypersensitivity, and Serology*. Appleton-Century-Crofts, N.Y., 1953.
(28) Rivers, T. M. (ed.), *Viral and Rickettsial Infections of Man*, 2nd ed., Lippincott, Philadelphia, 1952.

(29) Sanders, T. E., *J. Iowa State Med. Soc.*, **31**, 51 (1941).
(30) Sherwood, N. P., *Immunology*, 3rd ed., C. V. Mosby Co., St. Louis, 1951.
(31) Smadel, J. E., Ley, H. L., Diercks, F. H., Paterson, P. Y., Wisseman, C. L., and Traub, R. *Am. J. Trop. Med. Hyg.*, **1**, 87 (1952).
(32) Spencer, R. R., and Parker, R. R., *Pub. Health Rept.*, **40**, 2159 (1925).
(33) U.S. Dept. Agriculture, Animal Inspection and Quarantine Branch, Notice No. 312-B, U.S. Veterinary Licenses in Effect January 1, 1953, and Other Information Regarding Licensees and Biologics.
(34) U.S. Department of Health, Education and Welfare, Biological Products, Public Health Service Publication No. 50, Revised, Dec. 1, 1952.
(35) Weigl, R., *Bull. intern. acad. polon. sci., Classe sci. math. nat., Sér. B*, **1930**, 25.
(36) U.S. Pat. 2,518,978 (Aug. 15, 1950), H. Koprowski and H. R. Cox (to American Cyanamid Co.).

GENERAL REFERENCES

(37) Boyd, W. C., *Fundamentals of Immunology*, 2nd ed., Interscience, N.Y.-London, 1947.
(38) Burnet, F. M., *Natural History of Infectious Diseases*, 2nd ed., Cambridge, Univ. Press London, 1953.
(39) Haurowitz, F., in Cole, W. H., (ed.), *Serological Approaches to Studies of Protein Structure and Metabolism*, Rutgers Univ. Press, New Brunswick, N.J., 1954.
(40) Smith, D. T., and Martin, D. S., *et al.* *Zinsser's Textbook of Bacteriology*, 9th ed., Appleton-Century-Crofts, N.Y., 1948.
(41) van Rooyen, C. E., and Rhodes, A. J. *Virus Diseases of Man*, 2nd ed., Thomas Nelson and Sons, N.Y., 1948.

D. M. WOLFE

VACUUM GAGES. See *Electronics*, Vol. **5**, p. 552; *Pressure measurement*; *Vacuum technique*, pp. 506–10.

VACUUM TECHNIQUE

Vacuum technology comprises a variety of techniques for producing, measuring, and employing gas pressures less than atmospheric pressure. Each technique is limited to a certain pressure range, and within a given range the selection of the proper equipment and method of operation depend on the process requirements. The unit of pressure commonly employed is the millimeter of mercury (abbreviated as mm. Hg), and standard atmospheric pressure is chosen as 760 mm. Hg (see *Pressure measurement*, Vol. **11**, p. 87). Because the range of pressures within the operating limits of a given pump or vacuum gage is usually several orders of magnitude, data on vacuum equipment and processes are frequently presented graphically on a logarithmic pressure scale. Many of the important applications of vacuum techniques involve pressures less than 1 mm. Hg, and pressures below 1 mm. Hg are expressed in terms of negative powers of ten. Pressures in the range from 1 mm. Hg to 10^{-3} mm. Hg are frequently expressed in microns of mercury (abbreviated μ Hg).

A pressure of 1 mm. Hg has been somewhat arbitrarily chosen as the boundary between the moderate-(low-)vacuum and the high-vacuum regions. Most applications of interest to chemical engineers fall in the region from 760 to 1 mm. Hg (24). However, in recent years there has been an increased application of high-vacuum techniques in chemical processing, such as molecular distillation, isotope separation, metallurgical processes (for uranium, titanium, zirconium, and magnesium), and freeze-drying of biological and pharmaceutical preparations.

Moderate-(Low-)Vacuum Techniques. Evaporation and distillation can be

carried on at lower temperatures when the gas pressure is reduced. The use of lower temperatures reduces the thermal decomposition hazard and the rate of corrosion of process equipment. The vacuum required depends on the vapor pressure of the material and the temperature above which decomposition or corrosion is excessive. Many materials, which cannot be distilled at or above atmospheric pressure, can be distilled without decomposition in the range from 1 mm. to 760 mm. Hg.

Vacuum pumps are sometimes used merely to create a pressure differential across material to be moved (for example, in filtration, lifting and circulation of liquids, and vacuum cleaners). In these applications little is gained by reducing the pressure below 5% of 1 atm. (or 38 mm. Hg). Since the vapor pressure of water at room temperature is about 20 mm. Hg, the presence of water may frequently be tolerated in such applications. One of the most important applications of moderate-vacuum techniques is the evaporation of water from solutions or moist solids at temperatures below 100°C. Moderate-vacuum systems are therefore classified as "wet" or "dry," depending on the presence or absence of water in the liquid phase. Wet systems can be pumped with "wet vacuum pumps," such as piston pumps employing water as lubricant and sealant or water jet pumps. Steam ejectors are also frequently used on wet systems. Dry mechanical vacuum pumps do not use water but in general employ some low-vapor-pressure liquid for lubrication of moving parts, sealing of valves, cooling, and for reducing the "harmful space" between piston and exhaust valve.

In the vacuum range from 760 mm. to 1 mm. Hg, pressures are measured by relatively simple mechanical or liquid level gages, such as the Bourdon tube, bellows, or diaphragm gages, and the mercury U-tube manometer (see *Pressure measurement*). Leak hunting may be performed without the aid of expensive leak detectors by immersing the equipment in a water tank or coating suspected areas with a film of soap solution and watching for bubbles while raising the internal gas pressure slightly above atmospheric. However, halide or helium type leak detectors can be used to locate both large and small leaks quickly (see p. 517).

High-Vacuum Techniques. When the pressure falls below 1 mm. Hg into the high-vacuum region, significant changes occur in the properties of the residual gas and vapors. The ability of air to transmit sound and to conduct heat begins to diminish rapidly with decreasing pressure, and high-voltage electric discharges change from an arc to a glow and finally black out.

The molecular mean-free-path, or average distance a molecule can travel in a gas before colliding with another molecule, varies inversely as the pressure and becomes of the order of magnitude of the diameter of ordinary pipe lines when the pressure reaches 10^{-3} mm. Hg. As collisions between gas molecules become less frequent than collisions with the walls, the rate of flow of gas through a pipe ceases to depend on the internal viscosity of the gas and depends only on the temperature and the geometry of the pipe. When the mean-free-path exceeds the dimensions of the apparatus, the gas molecules wander in straight paths from wall to wall, evaporating from each surface in a random direction, and are removed from the system only by a chance flight from some surface directly exposed to the mouth of the pump. This process is referred to as "free molecular flow" and requires relatively large-diameter pipes of minimum length to avoid throttling the pump.

At pressures below 10^{-3} mm. Hg, the chemical composition of the residual gas changes rapidly as the oxygen and nitrogen content becomes negligible, while water vapor, organic vapors, and other sorbed gases begin to evolve from the walls, gaskets,

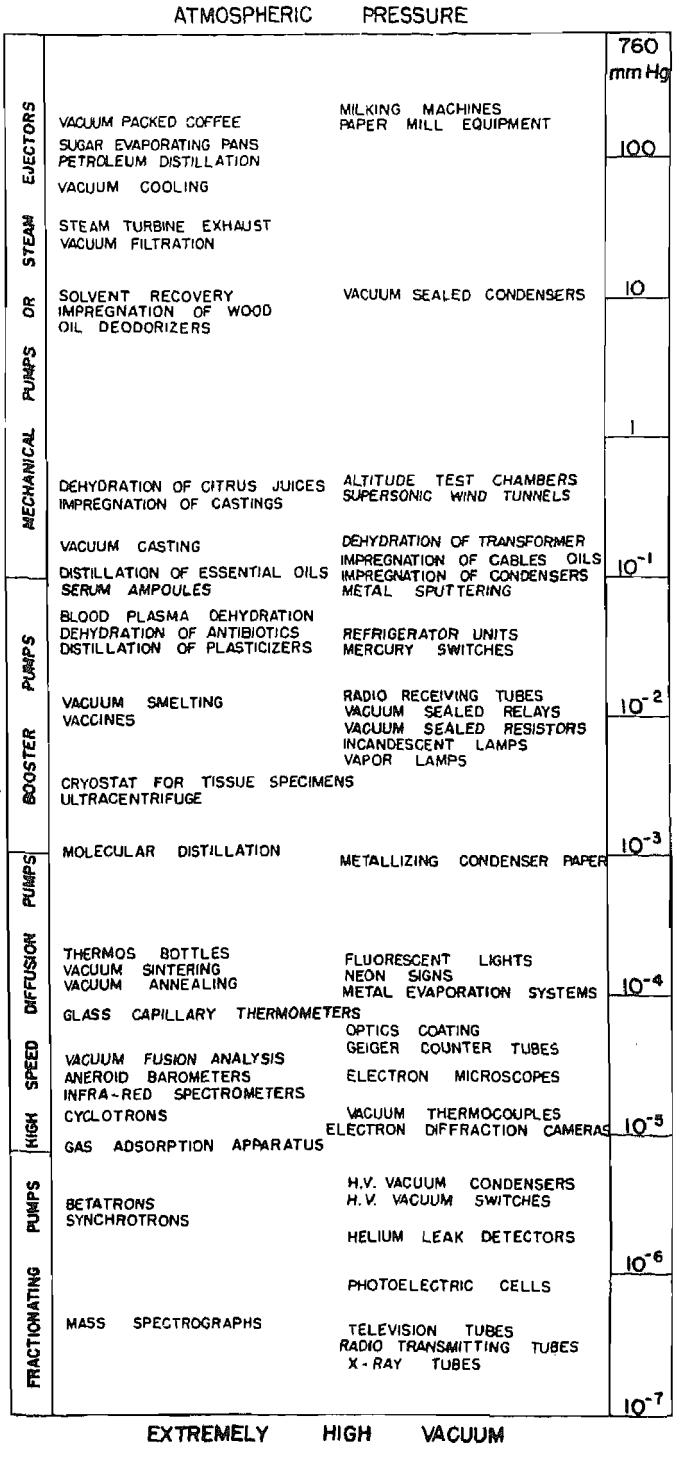


Fig. 1. Applications of vacuum.

and process materials in the system. To achieve pressures below 10^{-7} mm. it is necessary to limit the evolution of these vapors and gases by constructing the system of materials that can be outgassed readily by heating to around 400°C.

The ordinary high-vacuum region may be defined as the pressure range from 1 mm. to 10^{-7} mm. Hg, since modern high-vacuum equipment is available for producing and measuring pressures in this range on an industrial scale when suitable techniques are observed in designing and fabricating the vacuum system (7,9,16). This equipment includes oil and mercury diffusion pumps, ejector pumps, and special mechanical pumps for high-vacuum service which will be described in the following sections. High-vacuum gages are relatively complicated electrical or mechanical devices requiring special operating and calibrating techniques to avoid large errors in measurement. Some of the common vacuum gages and the techniques for leak detection in high-vacuum systems will be described (see also Vol. **5,** p. 594).

Several of the principal high-vacuum applications are arranged in chart form in Figure 1 according to the approximate pressure required in the vacuum system. Applications of importance as unit processes in chemical engineering will be described briefly. For a description of the sputtering and evaporation of metals and the evaporation of metallic salts under vacuum to form high-reflectance metallic coatings and low-reflectance salt coatings on glass and other materials, see *Silvering.*

Ultrahigh-Vacuum Techniques. Techniques have been developed for producing and measuring pressures considerably below 10^{-7} mm. Hg for such purposes as the study of surfaces free of adsorbed gas or the obtaining of very pure gases (1). By using systems constructed entirely of metal and glass, which can be baked in an oven at 400–500°C., and by cleaning up residual gases with ionization pumps and absorption traps, pressures as low as 10^{-12} mm. Hg can be reached. These techniques may find application in the electronics industry, but at present they are of limited application in chemical technology. See *Vacuum tubes.*

Measurement of Low Pressures

See also *Electronics*; *Pressure measurement*; references (3,9,16,33). The range of several common types of vacuum gages is illustrated in Figure 2. The width of the band is a rough indication of the variation in precision of readings over the useful range of a given gage but is not intended to indicate the relative accuracy of different gages. The ranges shown are somewhat arbitrary since modifications in design or operating conditions can shift the ranges up or down to some extent.

Liquid-level gages, such as the U-tube manometer and the McLeod gage, measure the pressure directly, and their calibration can be determined from the geometry of the instrument and the density of the liquid. These gages are constructed of glass and are easily broken and cumbersome to use, but they are important as the primary standards against which the other types of gages must be calibrated. The other gages are more convenient because they are usually provided with dials or scales on which the pressure is indicated by a pointer, but in general they do not have the same calibration factor for all gases and are subject to electrical and mechanical defects.

The mercury and butyl phthalate **manometers** usually have the form of a simple glass U-tube with means for providing a reference vacuum over the liquid in one arm. While *n*-butyl phthalate is the fluid most commonly employed in oil manometers, other nonviscous low-vapor-pressure oils of known specific gravity may be used. The

sensitivity of these manometers can be increased by inclining the measuring arm at a small angle with the horizontal or by measuring the meniscus level with a vernier or micrometer head attached to a pointed vertical rod inside one arm. The range depends on the lengths of the arms, the density of the liquid, and the reference pressure.

A typical **McLeod gage** is shown in Figure 3. Mercury in a reservoir is moved by the operator into a glass bulb compressing the gas trapped in the bulb into a closed capillary attached to the top of the bulb. The mercury rises simultaneously through a side arm attached below the bulb into an open capillary located adjacent to the closed capillary and of equal bore. The difference in mercury level in the two capillaries is multiplied by the volume of the gas trapped in the closed capillary and divided by the volume of the closed capillary and bulb to the cut-off (or side arm junction) to give the

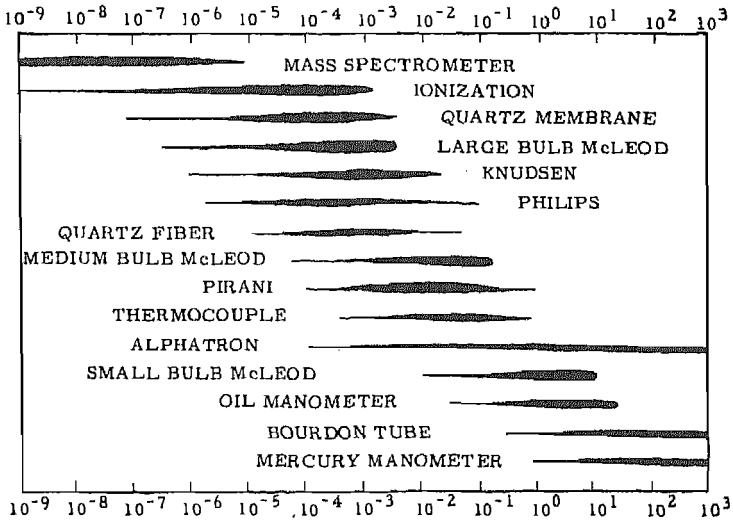


Fig. 2. Range of vacuum gages.

original pressure of gas in the bulb according to Boyle's law. The gage cannot be used for gases or vapors that condense at the prevailing pressures and temperatures. A solid carbon dioxide or liquid nitrogen trap must be included in the connecting line if the mercury vapor from the McLeod gage is to be kept out of the system or if vapors in the system are likely to contaminate the McLeod gage. The use of these traps is essential when calibrating other types of gage against the McLeod gage.

McLeod gages can be designed to cover, on one scale, a range of 3 or 4 cycles on the log scale of Figure 2 with the lower end of the useful range located at any point from 5×10^{-7} mm. to 1 mm. Hg. The double-range McLeod gage employs a second bulb of smaller volume located near the base of the closed capillary as shown in Figure 3. By bringing the mercury meniscus to a zero reference line located between the bulbs, the pressure is indicated by the position of the meniscus in the open capillary on a linear scale. The second range is obtained by bringing the meniscus in the open capillary to a zero reference line at the top of the closed capillary (Figure 3) and noting the position of the meniscus in the closed capillary on a direct-reading scale. The pressure reading, p, on this scale, follows the quadratic relation $p = kh^2/(1 - kh)$, where k is a constant and h is the distance between the zero reference line and the scale reading.

For brief descriptions of the hot-filament ionization thermocouple, Pirani, Bourdon, Alphatron, and diaphragm gages see Vol. **11**, p. 87 and Vol. **5**, p. 594. In the operation of the **Knudsen or radiometer gage,** a suspended vane system is rotated by directing gas molecules evaporated from a hot surface against one side of the vane while less energetic molecules coming from a cool surface impinge on the opposite side.

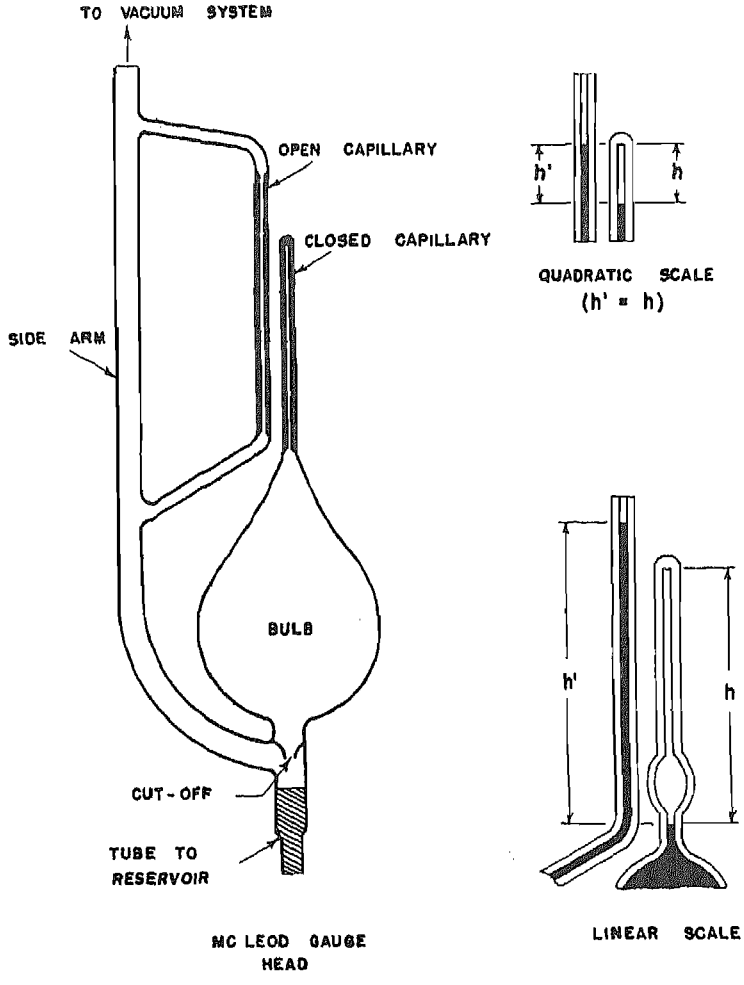


Fig. 3. McLeod gage.

The calibration of the Knudsen gage varies slightly with different gases because of differences in the accommodation coefficient and other factors. However, it has a great advantage over the McLeod gage in that it indicates the presence of condensable vapors. Since the heater temperature may be less than 100°C., the Knudsen gage does not decompose organic vapors like the hot-filament ionization gage. The response to changes in pressure can be made rapid but in general is slower than that of the ionization gage or a Pirani gage with very fine filaments. The gage requires careful mounting, and vibration must be suppressed by the dampening action of magnets.

The **hot-filament ionization gage** can be calibrated for various inert gases but is

not reliable with oxygen, hydrogen, carbon dioxide, and other active gases and vapors that are decomposed by chemical action or pyrolysis at the surface of the incandescent filament. The gage responds rapidly to changes in pressure, but the indicated pressure change is likely to be quite inaccurate at the lower pressures because of the liberation of miscellaneous molecules from the walls of the plate (ion collector) as the positive ions are embedded in the walls at amazingly high speeds. The error may be positive or negative, depending on the relative rates of "getter action," or "clean-up" of the positive ions, and the outgassing of the walls and electrodes. Large errors are often introduced when the connecting pipe between the system and the gage head is long and narrow so that the flux of molecules into the gage tube is not large compared with the clean-up of molecules or fragments of decomposed molecules by the filament and ion collector. Techniques for measuring the currents in ion gage tubes are explained in the operating instructions supplied with the various electrical control circuits available from vacuum equipment manufacturers.

The principle of the **Philips gage,** also called the cold-cathode ionization gage or Penning gage, is the measurement of the current transmitted through a glow discharge in the gas between a wire loop anode and two disk-shaped cathodes located above and below the plane of the anode at potentials of about 2,000 volts in the presence of a magnetic field. The direction of the magnetic field is parallel to the axis of the loop so that the electrons travel in long spiral paths as they move toward the anode. This action increases the possibility of collision with the gas molecules present, produces greater sensitivity, and sustains the glow discharge at lower pressures where the electron mean-free-path greatly exceeds the distance between electrodes. The Philips gage has two advantages over the hot-filament ionization gage. Since the cathode is cold, there is nothing to burn out when the tube is accidentally exposed to high pressures. Also, the Philips gage can be used to cover the important range from 10^{-6} mm. to 10^{-1} mm., whereas the ion gage cannot be used above 2×10^{-3} mm. However, the Philips gage is not as reliable as the ordinary ion gage because the parts of the tube are more difficult to outgas and the "clean-up" effect is intensified by the high voltages. The gage should not be exposed to mercury vapor.

The **Alphatron gage** uses the α-particles from a radioactive source to ionize the gas. It has the widest range of any of the electrically operated gages, recent designs operating from 1000 mm. Hg to less than 10^{-4} mm. Hg. It has no filament to burn out and does not suffer from the clean-up effects present in other types of ion gages.

The **quartz fiber** or **membrane viscosity gages** and all-glass gages of the **Bourdon** type are available for accurate measurements on extremely corrosive gases such as chlorine, but they are too fragile and tedious to operate for ordinary industrial use. Descriptions of these gages are given in references (1a,9).

The **Pirani** and the **thermocouple gages** may be calibrated for practically any gas or vapor that might be present within a vacuum system. The hot filament usually consists of a metal that is not easily attacked by most gases at the temperature employed. It is not safe to operate a Pirani or thermocouple filament at temperatures above 250°C. if organic vapors from the common greases, oils, and gasket materials are exposed in the system. Decomposition of these vapors on the filament usually leaves a dark deposit which seriously alters the sensitivity and the zero balance of a Pirani by increasing the emissivity of the surface. Pirani and thermocouple gages are excellent for indicating changes in pressure and the approximate value of the true pressure between 10 and 200 μ. However, they are not to be trusted in the 0–10 μ range or above

200 μ unless calibrated by an experienced operator on a vapor-free system a few hours before using.

Production of Low Pressures

The pressure of gas in a system at a given temperature may be lowered by allowing the gas to escape into a vacuum pump or by exposing a surface that retains impinging gas molecules by sorption or chemical forces. In very rare cases it has been found expedient to accelerate the movement of the gas toward the pump or trapping surface by ionizing the molecules and applying an electric field. Pumps employing ionization or sorption may be attached to the system.

The pressure within a closed system of fixed volume containing a large percentage of condensable vapor can be greatly reduced by cooling the walls to a temperature at which the vapor pressure is negligible. This principle is employed in the steam turbine in conjunction with pumps to remove the residual air. In all pumping systems some cooling of the walls is necessary to remove the heat of compression and the heat of condensation of any vapors to be condensed in the pump. In some systems, refrigerated traps are used to condense vapors before reaching pumps whose efficiency might be impaired by condensation of the vapor within the pump.

The *compression ratio* is defined as the ratio of exhaust pressure to intake pressure at a given load when pumping a gas or a vapor that is not condensed by the pump. This ratio is a variable quantity which depends in general on the ratio of the pumping speed to the speed of the forepump or next stage of compression.

The *pump speed* is defined as the volume of gas that flows into the pump in unit time at a constant pressure measured near the intake port. In high-vacuum technology speed is frequently expressed in liters per second or in cubic feet per minute. (One liter per second equals 2.12 c.f.m.)

Some high-vacuum pumps eject pump fluid vapor back into the system even while pumping gas, and all pumps have a minimum pressure which they can produce under standard test conditions known as the *ultimate pressure* or *ultimate vacuum.* Since this ultimate pressure is dependent on the balance between rate of flow of material in and out of the pump across the intake port, the above definition of pump speed requires clarification when the pressure decreases to a value near the ultimate pressure.

Throughput is defined as the quantity of gas in pressure-volume units per unit time flowing through the pump at a given intake pressure. The *speed of exhaust* is defined as the throughput of gas divided by the total pressure of gas and vapor measured near the intake port (8). Throughput is commonly expressed in micron-liters per second or micron-cubic feet per minute. The terms *load* and *capacity* are sometimes used to refer to the quantity of gas in mass units per unit time flowing through the pump at a given intake pressure. A load of one pound per hour of air at 25°C. corresponds to a throughput of 80,500 micron-liters per second.

The speed of exhaust, E, approaches zero as the pressure, P, approaches the ultimate pressure, P_0, according to the formula:

$$E = S(1 - P_0/P) \tag{1}$$

where S is the pump speed as defined above. The value of the ultimate pressure, P_0, is frequently limited to the vapor pressure of the pump fluid. The rate of decrease

in pressure in a chamber of volume V directly connected to a pump will be given by:

$$dP/dt = -EP/V \tag{2}$$

where E is the speed of exhaust at the pressure P. If the pump speed S in equation (1) is nearly constant over the pressure range P_1 to P_2, then substituting (1) in (2) and integrating gives a formula for the time of evacuation from P_1 to P_2:

$$t_2 - t_1 = \frac{2.3V}{S} \log_{10} \frac{P_1 - P_0}{P_2 - P_0} \tag{3}$$

The vapors evolved from vacuum systems can sometimes be passed through pumping stages of limited compression ratio without condensing, but in mechanical or multistage pumps of high compression ratio the vapor may be condensed. If the condensed vapor is the same as the working fluid in the pump, such as water vapor condensed in wet vacuum pumps, no harm is done, provided the fluid level is maintained at the optimum working value. If the condensed vapor can be separated from the working fluid by centrifuging, evaporation, or settling, suitable separating means can be added to the pump. If separation cannot be satisfactorily accomplished during operation of the pump, the vapor may be condensed in cold traps or liquid absorption columns before reaching the pump. In certain types of rotary pumps the Gaede gas-ballast principle (27) may be employed to avoid condensation by admitting air during the compression cycle.

The production of low pressures by adsorption, absorption, chemical reactions, or electrical clean-up is, in general, limited to high-vacuum and ultra-high-vacuum applications, such as the use of a barium "getter" in the production of radio receiving tubes. When no sorption or gettering is used, the lowest pressure attainable with a given pumping system and the rate of rise of pressure in sealed-off vacuum systems depends on the rate of evolution of gases and vapors within the system and the rate of inleakage from the atmosphere.

At pressures below 1 mm. Hg the rate of leakage through the walls of a system is substantially independent of the internal pressure. The partial pressure of air in the system due to leaks will then be inversely proportional to the pumping speed. The partial pressure of gas and vapor evolved from materials exposed in the vacuum system will depend on the areas exposed, the nature and previous treatment of the material, and the pumping speed. Because the diameter of the pipe between pump and system is often limited by practical considerations, more can sometimes be accomplished in attaining low limiting pressures by the proper selection of the materials to be exposed in the system than by increasing the pumping speed. Data on the relative outgassing rates of different materials have been published (6,23,47), but differences in measuring techniques make it difficult to compare values given by different authors.

Good vacuum technique consists largely in the use of materials of sufficiently low outgassing rate; the proper selection and matching of pumps, system, and pipe lines; and the design of flanges, gaskets, couplings, and welds so that leakage is reduced to a minimum and leak hunting is facilitated. However, even well-designed systems sometimes fail to reach the required low pressure, and certain vacuum techniques must be followed to diagnose and correct the trouble. These techniques involve the use of measuring and control instruments such as vacuum gages, leak detectors, thermometers, liquid-level indicators, valves, and heater power controls. A skilled technician can also tell much about the operation of pumps by listening to the sounds emitted and

feeling the temperature of the walls at certain points or noting the appearance of the pump fluid in pumps with glass walls or windows.

VACUUM PUMPS

The first practical vacuum pumps were developed by Otto von Guericke and Robert Boyle during the years 1640–1670. These pumps employed a moving piston fitting tightly in a cylindrical casing and having check valves that permitted the gas to flow only in the desired direction. These pumps were greatly improved by Fleuss (1890) who provided a quantity of oil in the exhaust end of the pump cylinder to reduce the "harmful space" at the end of the piston stroke so that less gas remained unexpelled through the exhaust valve. Various pumps employing liquid mercury as a

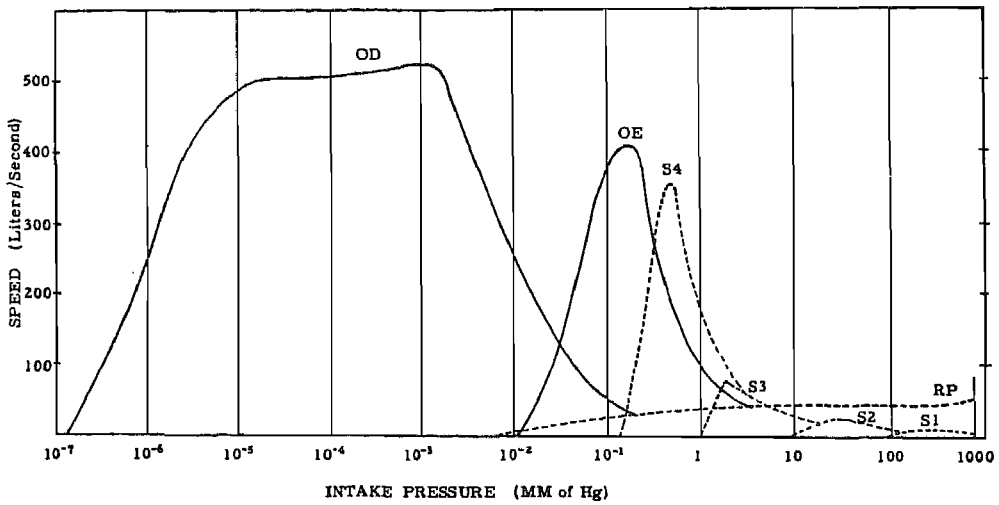


Fig. 4. Speed curves for typical pumps. OD—oil diffusion pump, three-stage fractionating type. OE—oil ejector pump, single-stage. S1, 2, 3, 4—steam ejector pumps, matching stages. RP—rotary piston oil-sealed mechanical pump, single-stage.

moving piston or a check valve were developed by Geissler (1855), Toepler (1862), Sprengel (1865), Kaufmann (1905), Gaede (1905), and others. Gaede developed the oil-sealed rotary piston mechanical pump in 1906. Finally, vapor jet pumps employing high-velocity streams of vapor discharged from nozzles into ducts of such cross section that the gas cannot readily flow countercurrent to the stream were developed. Steam ejector pumps were invented by Parsons (1902) and Leblanc (1908). Mercury vapor diffusion pumps were invented by Gaede (1915), Langmuir (1916), and Crawford (1917). Oil vapor diffusion pumps were invented by Burch (1928), Hickman (1929), and others. The oil ejector pump was developed by Hickman and Kuipers in 1941.

Modern vacuum pumps are of seven general types: (*1*) reciprocating piston pumps, (*2*) rotary piston pumps, (*3*) centrifugal pumps, (*4*) liquid jet pumps, (*5*) rotary blower pumps (turbine wheel and two- or three-lobe gear pumps), (*6*) molecular drag pumps, and (*7*) vapor jet pumps (ejector and diffusion pumps). Some vacuum pumps, such as types (*1*) through (*5*) can be designed to discharge gases directly into the atmosphere, while others require a *backing pump* or *forepump* to maintain a suitably low forepressure on the discharge side. Mechanical piston pumps

can be built with high compression ratios and made to operate over a wide pressure range. Single-stage vapor jet, molecular drag, centrifugal, and rotary blower pumps have a relatively low compression ratio at full load and require backing pumps to produce pressures in the high-vacuum region. Pumping stages of limited compression ratio are frequently combined in series within a common pump housing to give a *multistage* pump of broad operating range. The compression ratio for single-stage ejector pumps is about 10, and the compression ratio for individual stages of multistage diffusion pumps is about 4 at maximum throughput. The oil ejector and the diffusion pump cannot discharge gases directly into the atmosphere but always require a backing pump to produce the necessary forepressure.

The types and average operating range of some commercially available pumps are listed in Table I. The upper and lower limits of the operating range of each type of pump depend on the individual pump design, working fluid, and operating conditions. The values in Table I are, therefore, somewhat arbitrary. Actual performance curves for typical pumps are shown in Figure 4.

Vapor jet pumps have a *limiting forepressure* above which the pumping action is impaired by the gas in the forevacuum pushing the vapor jet away from the wall of the

TABLE I. Operating Ranges of Some Commercially Available Pumps.

Type of pump	Operating range, mm.
Reciprocating piston:	
Single-stage	760–10
Two-stage	760–1
Rotary piston oil-sealed:	
Single-stage	$760–10^{-2}$
Two-stage	$760–10^{-3}$
Centrifugal multistage (dry)	760–200
Liquid jet:	
Mercury Sprengel	$760–10^{-3}$
Water aspirator (18°C.)	760–15
Two-lobe rotary blower	$20–10^{-3}$
Molecular drag	10^{-1} to 10^{-5}
Vapor jet pumps:	
Steam ejector:	
1-stage	760–100
2-stage	760–10
3-stage	760–1
4-stage	760 to 3×10^{-1}
5-stage	760 to 5×10^{-2}
Oil ejector:	
1-stage	$2–10^{-2}$
2-stage	$10–10^{-2}$
Mercury diffusion with trap:	
1-stage	10^{-1} to $<10^{-6}$
2-stage	1 to $<10^{-6}$
3-stage	10 to $<10^{-6}$
Nonfractionating oil diffusion:	
1-stage	10^{-1} to 5×10^{-6}
2- and 3-stage	5×10^{-1} to 5×10^{-6}
Fractionating oil diffusion:	
Without trap, 3-stage	3×10^{-1} to 10^{-7}
With liquid nitrogen trap, 3-stage	3×10^{-1} to 10^{-11}

pump casing so that gas can leak back into the high vacuum. For diffusion pumps this limiting forepressure is approximately one-half of the *take-hold pressure* below which pumping action begins. The upper limit of the ranges shown in Table I for vapor jet pumps represents the take-hold pressure for the last stage of compression. The lower limit represents the *ultimate pressure* obtainable with typical pump fluids as measured on an untrapped gage of the type that reads total pressure of gas and vapors. When no traps are used, the ultimate pressure of oil and mercury diffusion pumps can never be lower than the vapor pressure at room temperature of the pump fluid that condenses on the walls near the intake port.

For the principles of construction and operation of mechanical pumps of the reciprocating piston, the rotary piston, the rotary blower, and the centrifugal types, see *Fluid mechanics (transportation)*; *Pressure technique (compressors and pumps)*. The molecular drag pump consists of a disk (Siegbahn type) or a cylinder (Holweck type) rotating at several thousand r.p.m. in a close-fitting housing containing a spiral groove in which the gas molecules are caused to flow toward a suitable forepump by the forward momentum received each time they collide with the rotating member. Improved molecular pumps of the Siegbahn or Holweck type are used in Europe but are rarely used in the U.S.

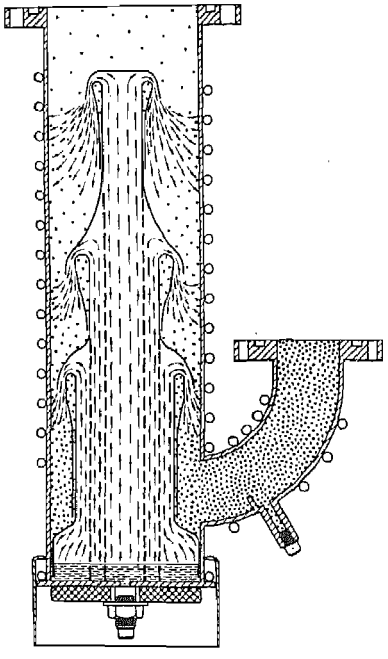


Fig. 5. Oil diffusion pump.

For a description of steam jet pumps, or *steam ejectors* (11,25,35,43a), see Vol. **5,** p. 938. Water jet pumps, or water aspirators, are commonly employed in the chemical laboratory but are seldom used on an industrial scale because of the large flow of water required (about one cubic foot of water for each cubic foot of gas pumped). Hydrosteam pumps are available in which the condensing water for one or more stages of steam ejector is recirculated through a water jet pump acting as forepump. Liquid mercury jet pumps of the Sprengel type are rarely used today except for handling small quantities of gases which would react with organic liquids or water and which must be pumped from a vacuum system into storage tanks or reaction vessels at pressures above 10 mm. Hg. Automatic Toepler pumps may also be used for this purpose. Vapor jet pumps employing oil or mercury vapor are described in the following sections.

Operation of Diffusion Pumps. A typical oil diffusion pump constructed of metal is shown in Figure 5. (The dashed lines show the modification necessary to convert to a fractionating type of pump.) The liquid in the bottom of the pump (or the boiler) is heated to temperatures in the range 150–220°C. causing vapor to evaporate from the upper surface (bubbles do not form as in ordinary boiling) at a rate sufficient to create boiler pressures in the range 0.3–1.0 mm. Hg. The vapor passes upward inside the "chimney" and is accelerated to supersonic velocities as it expands through the nozzles. The nozzles direct the vapor downward, but the vapor diverges outward toward the cooled pump casing as shown by the arrows. Also, some vapor is scattered

back toward the intake port. Gas molecules from the system can diffuse downward through this "backstreaming" vapor and penetrate into the denser forward-moving core of the vapor jet. Here they are driven at an acute angle toward the wall and on into the forevacuum. Because of the density and velocity of this forward moving stream, it is almost impossible for gas molecules from the forevacuum to diffuse upstream through the vapor jet and escape into the high-vacuum system.

There is always a small quantity of backstreaming vapor which is scattered from the top jet through the mouth of the pump. This vapor condenses on baffles placed above the pump and then migrates slowly by reevaporation into the vacuum system. The ultimate pressure which the pump can produce is limited by the pressure of this vapor in the system. Hickman (19) discovered that this vapor pressure could be reduced to a minimum without using cold traps by introducing fractionation of the oil during operation of the pump. The basic principle of fractionating pumps involves circulating the condensed pump fluid in the proper sequence through a series of boilers, or boiler compartments, feeding vapor to the separate nozzles in a multistage pump. Thus, in Figure 5, by providing cylindrical conduits between the boiler and the nozzles as shown by the dashed lines, the boiler is divided into a series of compartments. The condensed oil vapor returns down the inside wall of the casing and, in fractionating models of the type shown, flows first into the outer boiler compartment. Here the dissolved gases and more volatile impurities evaporate faster than the heavier fractions and pass out the lower nozzle, where they can do no harm because the upper jets act as one-way valves to prevent migration of molecules backward into the vacuum system. The fluid is forced to circulate through the outer compartment and enter through a small hole at the bottom of the inside cylinder into the next compartment which feeds vapor to the middle jet. Here further purging of volatile impurities occurs and the heavier fractions are concentrated in the fluid which passes on to the compartment feeding the top jet. After this circulation process has continued for a few hours, the extremely volatile impurities will have been ejected into the exhaust pipe, or forevacuum arm, where an alembic or trap prevents the return of liquid impurities to the boiler, and the highest-boiling fractions will be concentrated toward the center compartments. Since the vapor scattered from the top jet into the vacuum system will have originated from a boiler compartment containing the better fractions, the partial pressure of vapor in the system will be considerably lower than that which would prevail if the fractionating compartments were omitted (19).

Metal diffusion pumps are now available commercially in sizes ranging from a casing diameter of 1 in. and a speed of a few liters per second to a casing diameter of 48 in. with a speed of about 40,000 liters per second. Air cooling can be used on the smaller pumps, but water cooling is to be preferred. Organic or silicone oils are preferred as pump fluids because in fractionating pumps they can produce ultimate pressures as low as 10^{-7} mm. Hg without cold traps, whereas mercury diffusion pumps always require a liquid nitrogen trap to produce pressures below 10^{-6} mm. Hg. Mercury vapor is toxic, and mercury vapor pumps are not recommended for vacuum systems in which foods or drugs are processed. Among the commonly used organic pump fluids are di(2-ethylhexyl)phthalate, petroleum fractions of average molecular weight between 300 and 400, and the chlorinated biphenyls (32). The organic diffusion-pump fluids will be decomposed when exposed to air pressures above a few mm. Hg without turning off the pump heaters. The boiler should therefore be allowed to cool to a safe temperature as recommended by the manufacturer before exposing to atmospheric

pressure, or the pump should be kept under vacuum by using valves and a by-pass system when admitting air to the process vessel.

Operation of Oil Ejector Pumps. A typical oil ejector pump is shown in Figure 6. The vapor leaves the boiler (*A*) through the pipe (*B*). (*C*) is the gas intake. The vapor is expanded through the nozzle (*D*) into the water-cooled diffuser (*E*). The gas is cleaned by the baffle (*F*), then removed by the forepump at (*K*). The pump fluid condenses and returns to the boiler through (*H*). (*G*) shows the working head. (*J*) shows the heavy lagging on the boiler and vapor pipe. The principle of operation of oil ejector pumps is somewhat similar to that of steam ejectors but differs in that some water cooling is required on the converging region of the diffuser to condense that part of the vapor stream that reaches the walls when the gas load is below the maximum value. The pumping action differs from that of a diffusion pump mainly because the gas pressure at the intake is high enough to prevent free expansion of the vapor jet,

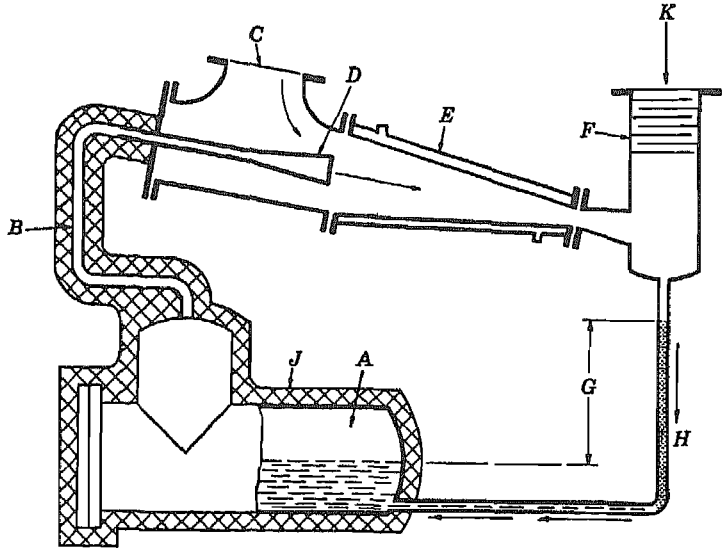


Fig. 6. Oil ejector pump (9).

and a relatively sharp boundary is formed between gas and vapor. The gas is entrained in the boundary layers of the vapor jet and is carried forward through the throat of the diffuser. Boiler pressures between 10 and 50 mm. Hg are normally used.

Oil ejectors are available in all sizes up to pumps with a 24-in. diameter intake having a speed of 5000 liters per second (13). They are widely used in chemical and metallurgical vacuum applications in the range from 10^{-2} to 1.0 mm. Hg.

Baffles and Traps. It is frequently difficult to reduce the partial pressure of vapors by pumping alone to values at which contamination of the system, or the product being processed, is negligible. In this case, some type of cooled baffle or trap must be installed. In all cases it is desirable to place a water-cooled or Freon-cooled baffle above the intake port of the diffusion pump in order to condense the backstreaming pump-fluid vapor and to return the fluid to the pump (38). If this is not done, the surfaces of the system directly exposed to the pump may become coated with a film of pump fluid, and the pump boiler may eventually be emptied by loss of fluid to the sys-

tem. The baffle must be optically tight so that no vapor molecule can pass through by molecular flow without striking a cooled surface, but the passages through the baffle must be wide and short so that the resistance to gas flow is not too large.

Leak Detection. It has been pointed out that the partial pressure of air in a system due to inleakage of atmospheric air will be inversely proportional to the net pumping speed when the total air pressure is below a few millimeters of mercury (see p. 511). In some applications it is not necessary to eliminate all of the small leaks in the system because suitable working pressures can be produced by employing high-speed pumps. However, in most applications there will be occasions when leaks occur which are too large to be tolerated. If the system is properly designed, the leak can be readily located by using one of the following techniques (9,16): (*1*) helium probe with a mass spectrometer focused for helium; (*2*) Pirani, thermocouple, or various types of ionization gages to detect inleakage of the probe gas such as acetone and hydrogen; (*3*) palladium barrier ionization gage with hydrogen as probe gas; (*4*) filling system with compressed air and coating with soap solution; (*5*) copper-plate halide flame indicator with Freon as probe gas; (*6*) hot platinum-ceramic couple as halide-sensitive, positive-ion emitter with halogen compound as probe gas; (*7*) differential Pirani or ionization gage using cold trap and condensable probe gas (4); (*8*) rate of rise of pressure in sections isolated by valves, plugs, cover plates, etc.; (*9*) high-voltage spark coil (Tesla coil) for glass systems; (*10*) ultraviolet absorption cell and organic probe gas (44).

There are a number of other methods which involve subjecting the inside of the system to liquids or chemically active gases. These latter methods are not recommended because the system becomes contaminated and must be thoroughly cleaned before a high vacuum can be produced. For a brief description of various electrical devices for leak detection see Vol. **5,** p. 595.

The mass spectrometer type of leak detector, which employs helium for the probe gas, is the most sensitive and accurate instrument. A complete unit with all accessories costs about $5000.00, and specially trained personnel are required for operation and maintenance, yet the time saved in finding leaks and avoiding shutdowns often justifies the use of this type of leak detector in industrial applications of large and complicated vacuum equipment.

Techniques for using the mass spectrometer leak detector on various types of vessels were developed during World War II and are fully described in various Manhattan Project reports (16,26). To use this method to best advantage, the process equipment should be designed with special double-gasketed flange joints for circulating helium as shown in Figure 10(*b*) and (*c*), or the flanges should have a raised face so that the gaskets are easily accessible to a helium probe, and sufficient test connections should be provided at strategic locations for attaching the intake line to the leak detector. The location of these latter connections should be so chosen that the ratio of the system volume to the pumping speed is not more than 10 seconds. After preliminary evacuation of the system with large pumps, the residual gases can be pumped directly into the leak detector using the small pumps within the latter. Or, the gases can be passed into an auxiliary pumping system consisting of a vapor jet pump and a mechanical pump with the leak detector connected to the "backing space" between the vapor pump and the mechanical pump. Helium from a standard cylinder with reducing valve is applied to the outside of the system under test by means of a long narrow metal tube with a fine orifice which directs a jet of helium at the points suspected of leaking. The

jet may be moved along a weld or flange at the rate of about one inch per second. When the helium enters a leak, a surge will be observed in the reading of the output meter or a sound of increasing pitch and intensity will be heard on units equipped with an audioindicator.

The over-all tightness of a system can be measured by the "hood method." This consists in surrounding the equipment with a hood of rubber or plastic, or a gas-tight box, in which a fixed concentration of helium is maintained, and comparing the output meter deflection with that obtained when the helium mixture is allowed also to flow through a calibrated leak installed under the hood. The smallest leak rate that can be detected with the helium leak detector is about 10^{-10} ml./sec. of air at S.T.P. Large leaks require auxiliary pumping systems to lower the pressure to 0.1 mm. or less, and the throttle valve on the leak detector is adjusted to maintain pressures of 10^{-4} mm. Hg or less in the mass spectrometer tube. Sampling probes are also available which draw helium mixed with air at atmospheric pressure into the leak detector when placed near a leak in a system filled with helium at 10–20 p.s.i. gage pressure.

When minute traces of certain organic vapors, especially those containing a halogen, come in contact with a hot platinum anode that has been sensitized by a source of alkali ions, the ability of the platinum to emit positive ions is greatly increased. There are two methods of using this phenomenon for leak detection. The system under test may be filled with gas containing a halogen compound, such as Freon, at pressures above atmospheric and the gas escaping through a leak can be drawn into the detector by a small motor-driven fan (46). The sensitive platinum element can also be placed in a glass or metal envelope with a tubulation connected to the system, and the system evacuated while Freon is played over the suspected areas on the outside of the system. Freon entering through a leak will diffuse into the detector head. In this latter method the voltages must be limited so that glow discharges are avoided. It is claimed that the sensitivity of these halide leak detectors is nearly equivalent to that of the helium leak detector. However, these halide leak detectors are not as satisfactory as the helium type for quantitative measurements of leak rate.

Another type of halide leak detector, which is less expensive but also less sensitive, consists of an acetylene burner or a gas bunsen burner with the flame striking against a copper plate. The air intake to the burner is encased in a housing to which a long rubber hose is attached. The end of the hose is moved along the joint suspected of leaking. When the system is filled with Freon under pressure, the Freon gas that escapes through a leak and is drawn into the burner reacts with the hot copper plate. Traces of Freon cause a greenish color to appear in the flame while large quantities of Freon impart a violet color to the flame.

In using Freon as the probe gas it must be remembered that Freon-12 is about four times as heavy as air. Therefore, probing should be started at the bottom of the system and continued upward. In some cases it is convenient to fill the system with pure Freon and then recover the Freon by pumping it back into the storage tank.

Design of Vacuum Systems

The design of vacuum pipelines requires a knowledge of the laws governing the flow of gases in the four regions distinguished by the names turbulent flow, viscous flow, transition flow (between viscous and molecular flow), and molecular flow. Poiseuille's law holds for the viscous flow of gases through cylindrical pipes (see *Fluid*

mechanics). Turbulent flow is seldom encountered in actual vacuum practice except for short periods during which the mean pressure in the pipe is only slightly lower than atmospheric. If the pipeline is designed to be adequate in the viscous flow range, it will be found adequate in the turbulent range. The flow of air at room temperature becomes turbulent when the throughput exceeds $2 \times 10^5 D$ micron-liters per second, where D is the pipe diameter in centimeters. The laws of flow in the transition and molecular flow regions were developed by Knudsen, Smoluchowski, and Clausing (9).

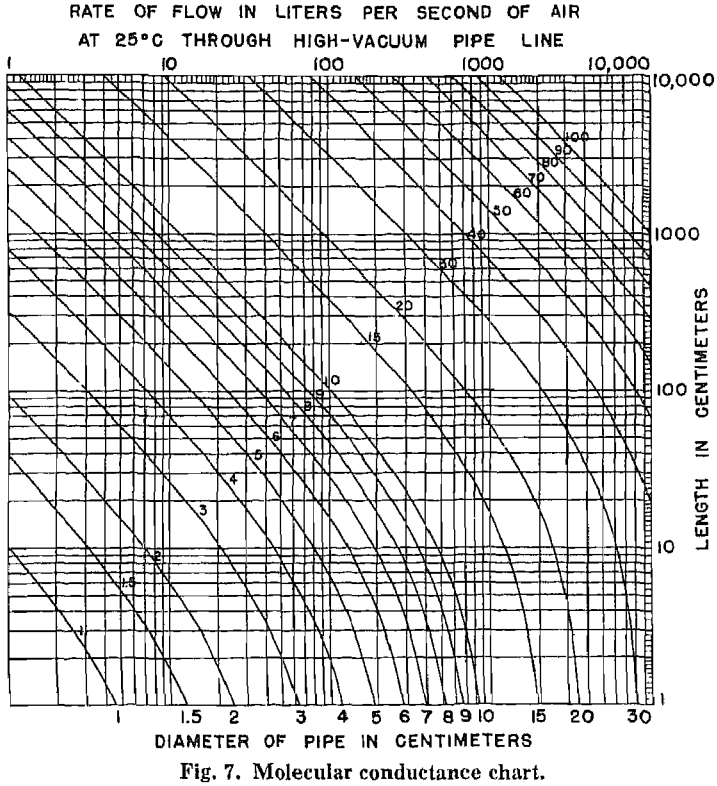


Fig. 7. Molecular conductance chart.

The Net Speed Formula. For a well-designed pipeline it is accepted practice that the net pumping speed S shall not be much less than 80% of the speed S_0 available at the mouth of the pump or at the entrance to the baffle (when the latter is not incorporated in the pump). The reduction in pumping speed depends on the *resistance*, or *impedance*, W of the pipeline. The formula for computing the net pumping speed, S, is:

$$\frac{1}{S} = \frac{1}{S_0} + W \tag{4}$$

where S and S_0 are usually expressed in liters per second and W in terms of seconds per liter. It is sometimes more convenient to use the reciprocal of the impedance, which is known as the *conductance* and is represented by $U = 1/W$. Then:

$$S = S_0 U/(S_0 + U) \tag{5}$$

Equations (4) and (5) are valid only when S_0 and U (or W) are suitably defined and measured (8).

Conductance of Circular Pipes. The conductance U is frequently expressed in liters per second, although to be strictly correct it should be considered as micron-liters per second per micron pressure difference across the ends of the tube. Conductance problems are conveniently divided into two classes, the molecular flow type, for which the product of the mean pressure $\bar{P}$ (one-half the sum of the entrance and

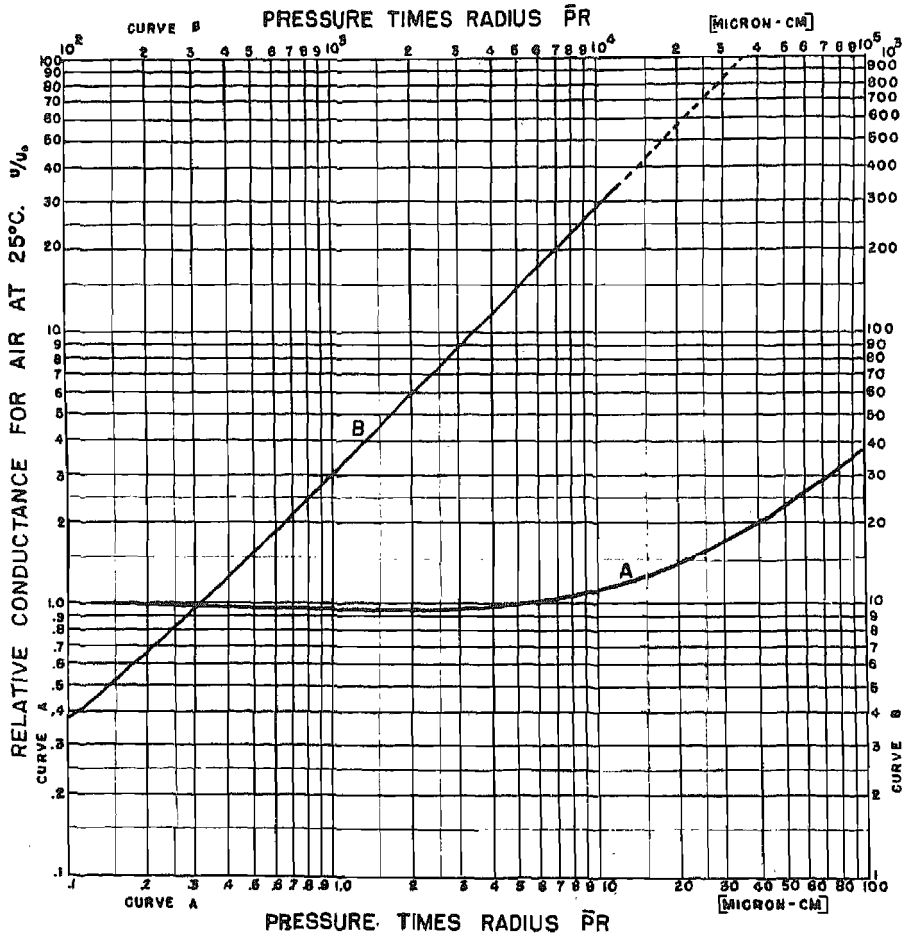


Fig. 8. Relative conductance factor chart.

exit pressures) in microns of air at room temperature and the radius R of the tube in centimeters is ten or less, and the Knudsen-Poiseuille flow type, for which the $\bar{P}R$ product is greater than ten.

Figure 7 gives the "molecular conductance" U_0 of air at 25°C. through a circular pipe of diameter D centimeters and length L centimeters located between two large chambers in which the pressure is P_1 and P_2, respectively. The mean pressure will be given by:

$$\bar{P} = (P_1 + P_2)/2 \tag{6}$$

and the product $\bar{P}R$ should be computed (in micron-centimeters) to determine whether the flow is molecular or not. Figure 8 gives the relative conductance factor U/U_0, or ratio of true conductance to molecular conductance, for air at 25°C. as a function of the $\bar{P}R$ product in micron centimeters according to Knudsen's formula (29). To obtain the true conductance U, the molecular conductance U_0 as given by Figure 7 is multiplied by the relative conductance factor U/U_0 as given by Figure 8. To find this factor locate the $\bar{P}R$ product on the horizontal axis. If the product is between 0.1 and 100, the value will be located at the bottom of the chart and curve A will be used. If the product is between 100 and 100,000, the top scale and curve B are used. For example, a $\bar{P}R$ product of 1,000 corresponds to a factor of 30. The conductance U thus obtained represents the rate of flow in micron-liters per second per micron pressure drop at the given mean pressure, although as previously noted the dimensions may also be interpreted as liters per second. To find the actual quantity Q of gas flowing through the tube in micron-liters per second, multiply this value of U by the difference in pressure at the two ends of the tube, thus:

$$Q = U(P_1 - P_2) \tag{7}$$

Figure 8 cannot be used when the flow becomes turbulent. The transition to turbulent flow occurs when the throughput exceeds $4 \times 10^5 R$ micron-liters per second, and for most systems this is likely to occur in the region on Figure 8 where curve B is represented by a broken line.

The molecular flow of air at room temperature through *long* cylindrical tubes may also be estimated from the approximate formula:

$$U_0 = R^3/L \tag{8}$$

where U_0 will be given in liters per second when the radius R and length L are expressed in *millimeters*. If the pressure is too high for molecular flow, then U_0 is computed from R^3/L or read from Figure 7 and the result is multiplied by the relative conductance factor as given by Figure 8.

If the pipeline is constructed of a series of long tubes of different diameters, the total molecular conductance U_0 in liters per second for air at room temperature can be computed from the formula

$$\frac{1}{U_0} = \frac{L_1}{R_1^3} + \frac{L_2}{R_2^3} + \frac{L_3}{R_3^3} + \cdots \tag{9}$$

where L_1 is the length in mm. and R_1 is the radius in mm. of the first section, etc. If the length of any section is less than ten times the diameter and the diameter changes abruptly at the entrance to this section, then a correction term for the entrance or aperture impedance of this section should be included. To correct for the entrance impedance of any section of pipe of cross-sectional area A_n square centimeters the term $(A_m - A_n)/11.7\, A_m A_n$ is added to the right side of equation (9), where A_m is the cross-sectional area in square centimeters of the chamber from which the air enters the section in question.

For the flow of gases other than air, the molecular conductance, U_0, as given by Figure 7 should be multiplied by $(28.98/M)^{1/2}$, where M is the molecular weight of the gas. For temperatures other than 25°C. the value of U_0 as given by Figure 7 should be multiplied by $(T/298.18)^{1/2}$, where T is the absolute temperature. Figure 8 for the relative conductance can be corrected for different gases and temperatures by multi-

plying the $\bar{P}R$ product by the factor $(1.83 \times 10^{-4}/n_i)(298M/297T)^{1/2}$, where n_i is the viscosity of the gas in poises, and locating this result on the horizontal axis instead of the original value of $\bar{P}R$.

The following method of changing the scale units permits Figure 7 to be used for tubes whose diameters are so small or so large that the point corresponding to the desired length does not fall on the chart. Multiply both the given length and diameter by 10, or some positive or negative power of ten, so that the point falls on the chart. Then the conductance read at the top of the chart must be divided by 100, or by the square of the power of ten chosen, to obtain the correct answer. For example, the conductance of a tube of 0.3 cm. I.D. and 10 cm. length is obtained by following the curve for a diameter of 3 cm. to the intersection with the line for a length of 100 cm. and reading 3 liters per second from the scale at the top. The correct answer is then 3/100 or 0.03 liter per second.

The resistance of a bend or elbow in the pipeline can usually be neglected for molecular flow, provided the length L is measured along the center line and the bend is not within two diameters of the end of the tube or another bend. For sharp bends located near the end of the tube or within two diameters of another bend, the effective length of the bend can be considered as it axial length plus one diameter. Formulas for the conductance of ducts of noncircular cross section will be found in references (5,9,16).

Assembly of Systems

The essential components of a typical large high-vacuum system employing vapor pumps are shown in Figure 9. The diffusion pump (*a*) must be located close to the

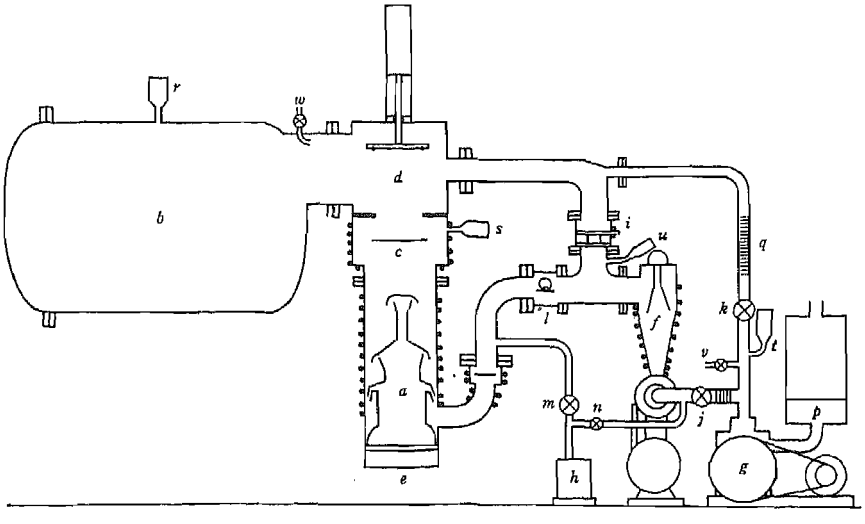


Fig. 9. Typical high-vacuum system.

vessel (*b*) and should always have a water-cooled or Freon-cooled baffle (*c*) located over the pump mouth so that backstreaming vapor will be condensed and returned as liquid to the pump. The high-vacuum valve (*d*) and manifold connecting the vessel and the baffled pump should be of diameter equal to or larger than the mouth of the pump, and

the length of the passage between the baffle and the vessel should preferably be not more than about three times the mean diameter of this passage. A space at least 6 in. high should be allowed below the diffusion pump boiler (*e*) for easy servicing of the heaters, draining the pump fluid, or removal of the pump from the system.

Selection of Pumps. The type of diffusion pump and pump fluid selected depends on the lowest pressure that must be attained (see Table I). The size of the pump depends on the gas load during the process cycle and must be determined from performance curves similar to Figure 4 as supplied in the manufacturers' catalogs. As a general rule the net pumping speed in liters per second at the entrance to the vessel should be of the same order of magnitude as the volume of the vessel in liters. (To convert volume in cubic feet to liters multiply by 28.3, or roughly by 30.) For most metal systems, a water-cooled, three-stage, diffusion pump will be employed, and the cooling water should circulate through the coils from the high-vacuum toward the fore-vacuum side at a rate in cubic centimeters per minute equal to the heater input in watts. The maximum throughput of such pumps in micron-liters per second is approximately equal to twice the heater input in watts. Automatic safety controls are available to protect against failure of the cooling water. Efficient cooling is particularly important for mercury vapor pumps. Air cooling is possible with oil vapor pumps but is not recommended except on portable systems.

Since diffusion pumps will only operate against a forepressure (pressure on the exhaust side) of about 0.5 mm. Hg or less, the pressure range from atmospheric to the limiting forepressure for the diffusion pump must be covered by a suitable "forepump" or "roughing pump." The oil-sealed rotary mechanical pump is the type most commonly used, but steam ejectors may be more efficient in some applications where high-pressure steam is available. The pressure range from 1 mm. to 10 μ may be covered by either an oil vapor ejector (*f*), or a mechanical pump. If a mechanical pump is in use and it is found that too much time is being spent in this pressure range because of evolution of gas from the system, then an oil vapor ejector should be installed.

The size of the mechanical pump (*g*) required depends primarily on the time allowable for covering the range from atmospheric pressure to a pressure of 0.5 mm. at which the typical diffusion pump begins to operate. This time can be estimated from the approximate formula:

$$t = 7V/S_f \tag{10}$$

where V is the total volume of the system and S_f is the average speed of the forepump (assumed constant over the whole pressure range). When V is given in cubic feet and S_f in c.f.m., then t will be given in minutes. When V is expressed in liters and S_f in l./sec., t is obtained in seconds. Thus, to pump a chamber of 10 cu. ft. from 760 to 0.5 mm. Hg in 7 minutes requires at least a 10-c.f.m. forepump. Since most mechanical pumps have an average speed about equal to $\frac{3}{4}$ of the rated speed or displacement at atmospheric pressure, a 14-c.f.m. mechanical pump would be recommended in this case. Formulas and graphs for estimating pump-down time will also be found in the manufacturers' catalogs for the various mechanical pumps.

The size of the forepump selected may depend on the peak load as well as the pump-down time. Every diffusion pump has a maximum micron-liter per second throughput determined by the jet design and operating conditions. However, if the speed of the forepump is not sufficient, the maximum micron-liter per second throughput of the diffusion pump will be limited to the product of the forepump speed and the limiting

forepressure for the diffusion pump. Since it is usually desirable to keep this product larger than the peak load of gas evolved from the vacuum system after the diffusion pump has begun to operate, the size of the forepump selected should be adequate to meet this peak-load condition. Frequently the size indicated by the peak-load condition is much smaller than the size required to meet the specified pump-down time. In this case, if the processing part of the cycle is much longer than the pump-down time, it is advisable to use two forepumps—a large one (g) for roughing down from atmospheric pressure and a smaller one (h) for holding the vapor pumps during the roughing period and backing them during the processing period.

Location of Valves, Traps, and Connecting Lines. Because of the long warm-up and cool-down times in some cases it is desirable to keep the vapor pumps hot by closing valves (d), (i), and (j) and operating the holding pump (h) while roughing down to 1 mm. Hg with the forepump (g). Valves (k) and (l) are then closed while (j) and (i) are opened and the holding pump is switched to the diffusion pump by valves (m) and (n) until the pressure in the vessel reaches 100 μ. Then (i) is closed while (d) and (l) are opened. When the time allowable for reaching 10^{-4} mm. is more than 20 minutes, the roughing can be done through the diffusion pump providing the boiler has been cooled to a safe temperature for exposure to atmospheric pressure. The time required to cool the boiler to the safe temperature can be shortened by passing cold water through the cooling coil which surrounds the boiler on certain of the smaller metal pumps. The pump heaters can be turned on again as soon as the vessel is roughed down to 500 μ. The use of this procedure obviates the need for high-vacuum valves, by-pass lines, and holding pumps.

Provision for separating water from the mechanical pump sealing oil (p) or for preventing condensation within the mechanical pump should be made whenever the system evolves large quantities of moisture. In extreme cases, a cold trap must be included in the forevacuum line to condense moisture or solvents which might contaminate the forepump.

Since the larger mechanical pumps often have considerable vibration, flexible metal bellows (q) are usually included in the forevacuum line. These bellows also aid in aligning the pipes during assembly. It is not necessary to have the mechanical pump or even the ejector pump installed close to the vessel and the diffusion pumps, since the resistance to gas flow of moderate lengths of pipe having the same diameter as the suction opening on these pumps is not a serious problem at pressures above 200 μ. In some installations it is desirable to locate the mechanical pumps at a distance for easy servicing without exposure of personnel to dangerous process equipment, or to reduce the noise level in the process room.

If the process involves a period of outgassing or there is a steady evolution of gas, the pressure that can be maintained is roughly inversely proportional to the net speed of the diffusion pump and connecting pipeline. When the outgassing load exceeds the maximum capacity of the diffusion pump, the jets "break down" and the pressure rises rapidly. If the heater is not shut off and the forepressure is not too high, the jet action may be resumed temporarily. However, the pressure oscillates over a wide range and the pumping action is unsteady. In some processes the period of outgassing is brief and the diffusion pump is allowed to run in the breakdown region until the pressure again falls to the point at which the process can begin. Oil vapor ejectors are extremely useful in shortening these periods. If the forepressure rises to more than 800 μ for more than five minutes, the heater of the diffusion pump should be

shut off to avoid decomposition of the oil. Automatic devices for shutting off the heater are available.

Installation of Gages and Controls. Referring to the typical large vacuum system illustrated in Figure 9, a hot-filament ionization gage or a Philips gage, or possibly a Knudsen gage, should be installed on the process vessel as shown at (*r*) and also on the baffle at (*s*) below the seat of the high-vacuum valve (*d*). If mercury vapor is present in the system, the gage may have to be trapped with liquid nitrogen or with solid carbon dioxide and acetone. The rate of rise of pressure on gage (*r*) when valve (*d*) is closed will indicate the leak rate or outgassing rate and give information about the presence of vapors.

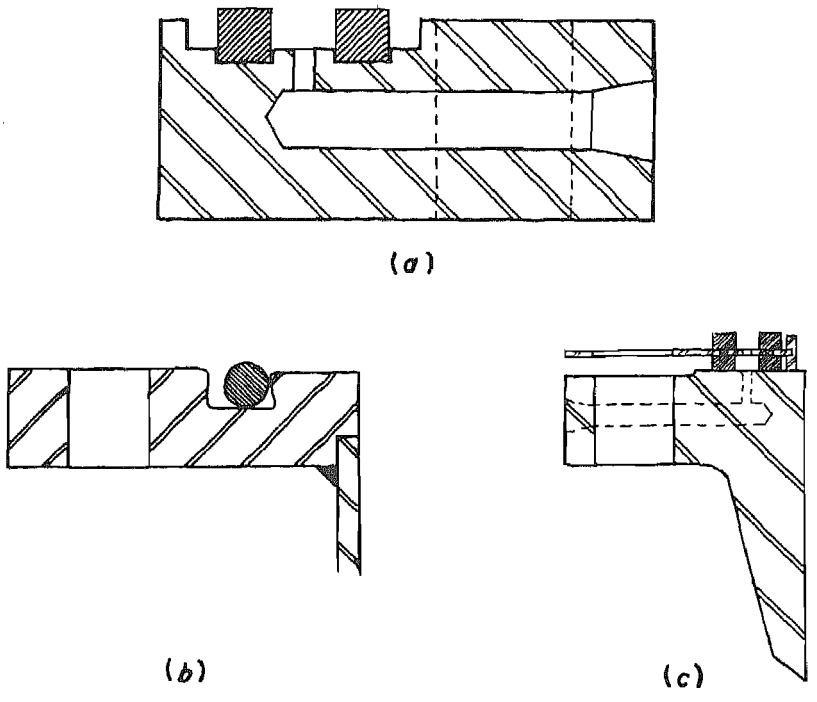


Fig. 10. Flange joints: (*a*) with double gasket groove; (*b*) with O-ring gasket; (*c*) with gasket insert.

A Pirani, thermocouple, or rotating-type McLeod gage should be installed in the forevacuum line at (*t*). A Bourdon-type gage can be installed on the vessel or in the forevacuum line if the progress of evacuation from atmosphere down to a few mm. Hg must be watched. The condition of the forepump can always be checked by closing valves (*j*) and (*k*) and observing the gage at (*t*). A Pirani or thermocouple gage can be installed at (*u*) when information on the interpump pressure is of interest (for example, when pumping hydrogen or any gas at interpump pressures near the limiting forepressure for the diffusion pump).

The valve at (*v*) is used to vent the forepump while holding the rest of the system under vacuum by closing (*j*) and (*k*). This should be done when shutting off the motor on the mechanical pump for a long period since the sealing oil may otherwise leak back into the vacuum system. This opening can also be connected to a leak detector, which may be of the halide sensitive or of the mass spectrometer type.

The process vessel should be vented through a valve located on the vessel as shown at (*w*). The blast of inrushing air should be directed away from the process material in the chamber. Air should never be admitted to the vapor pumps through the vent (*v*) in the forevacuum line when valve (*j*) is open and valve (*k*) is closed since the air

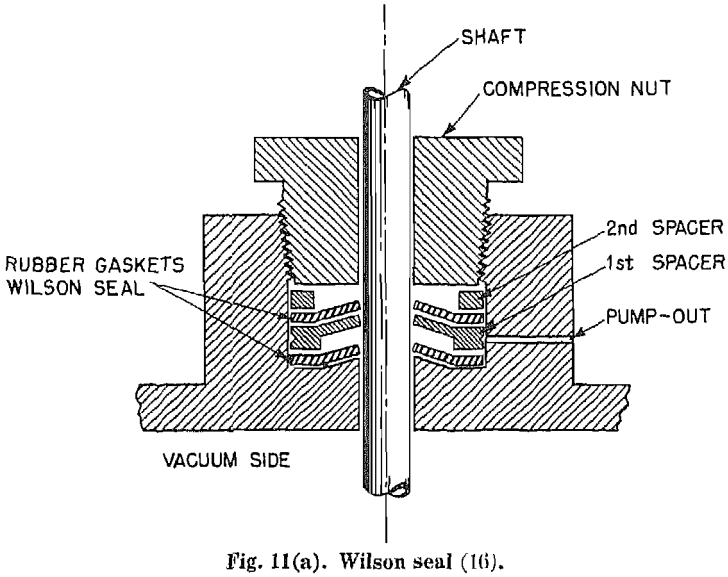
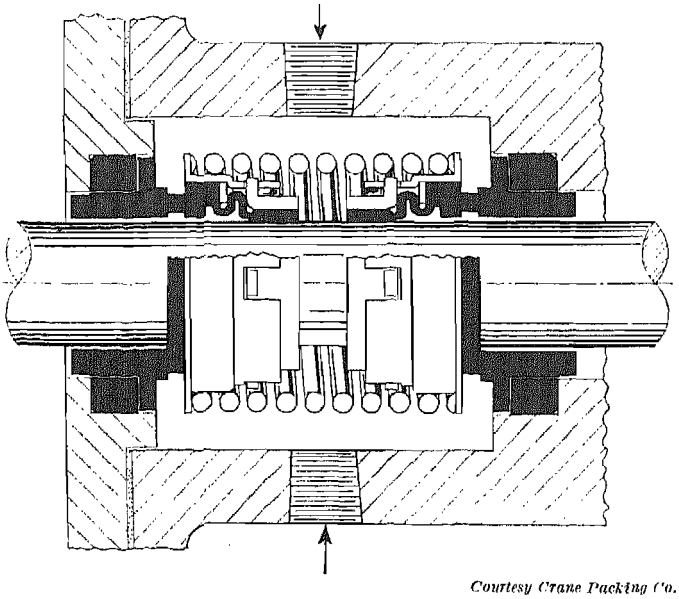


Fig. 11(a). Wilson seal (16).



Courtesy Crane Packing Co.

Fig. 11(b). Rotary shaft seal. Arrow indicates connection for lubrication circulation.

may carry oil vapor into the vessel or dislodge the jet assembly in the diffusion pump. The time, *t*, in minutes to vent a vacuum chamber of volume *V* cubic feet from pressures less than 1 μ to atmospheric pressure through a standard globe valve of nominal *diameter D inches is given approximately by*:

$$t = V/100D^2 \tag{11}$$

A thermal switch may be installed on the cooling coils of the vapor pumps to protect against failure of cooling water or may be located in the boiler to prevent overheating due to a forepressure above the critical value. A pressure-operated safety switch can be installed in the forevacuum line to protect the vapor pumps against excessive rise in forepressure. The mechanical pump should have a solenoid operator on the shut-off valve in the oil line. Pneumatic operators with fail-safe features can be installed on valves (*d*), (*i*), (*j*), (*k*), and (*l*). The control panel should have interlocks on the switches for the vapor pumps and high-vacuum gages to protect against operation under improper conditions.

Joints, Seals, Gaskets, and Valves. Figure 10 illustrates typical high-vacuum flange joints using O-ring rubber gaskets and square cross section rubber gaskets. The use of a double gasket (Figure 10(*a*) and (*c*)) permits leak hunting by supplying a tracer gas to the space between the gasket rings through the hole in the flange. This space can also be evacuated by an auxiliary pump to check for leakage past the inner gasket and temporarily stop the leakage until the system can be opened for repair of the leak.

Rotary shaft seals are shown in Figures 11(*a*) and 11(*b*). There are many types of vacuum valves, glass-to-metal seals, shaft seals, tubing couplings, electrode seals, and other vacuum plumbing accessories available. For details see references (16,24, 30,43).

Applications

Vacuum Distillation. Most organic compounds will not tolerate prolonged heating at temperatures greater than 250°C. without excessive decomposition. Compounds of molecular weight greater than 150 will in general have vapor pressures less than 760 mm. Hg at temperatures below 250°C. and must therefore be evaporated at reduced pressure by vacuum or steam distillation techniques. Steam distillation can only be used with materials that are immiscible and unreactive with water. Low pressure is also useful in the fractional distillation of mixtures that are azeotropic at atmospheric pressures. In some cases it is more economical to use low pressures in fractional distillation because less heat is required to achieve a given separation.

Vacuum-distillation techniques are classified by the type of still employed. *Molecular stills* are designed so that the distance between the evaporating surface and the condenser is not large compared with the mean-free-path of the vapor molecules; they operate at pressures of 0.01 mm. Hg or less. The material being distilled (distilland) is usually spread out in a thin film over the surface of the heating unit and caused to flow by gravity (*falling-film still*) or centrifugal force (*centrifugal still*) over the hot surface into a reservoir for the residue. When no obstruction is interposed between evaporator and condenser, the distillation is substantially "projective," that is, very few evaporated molecules return to the distilland. Short-path rotating drum stills, in which the distilland is spread in a thin film on a horizontal roller and the residue is scraped off before the surface again dips into the distilland, have been constructed in Germany (24).

The *open-path* or *short-path pot still* is not generally regarded as a "molecular still," but it does employ a short, wide rectification column with a very low pressure drop from pot to condenser. Stirring of the distilland in the pot is desirable since

ebullition does not occur in high-vacuum distillation. The *equilibrium pot still* employs a long, narrow column, or a wide column with stationary packing, or a concentric rotating condenser which flings the condensate back to the heated wall of the column. The fractionating efficiency is high, but the pressure drop and thermal decomposition hazard are also higher than for short-path stills.

For large-scale fractional distillation or rectification at pressures in the moderate-vacuum region (760 mm. to 1 mm. Hg), conventional bubble-cap plate towers and tubular boilers may be used. To avoid a pressure drop of more than 1 or 2 mm. Hg per tray, the slot submergence, or liquid head above the top of the slots in the bubble cap, must be maintained at a suitably low value.

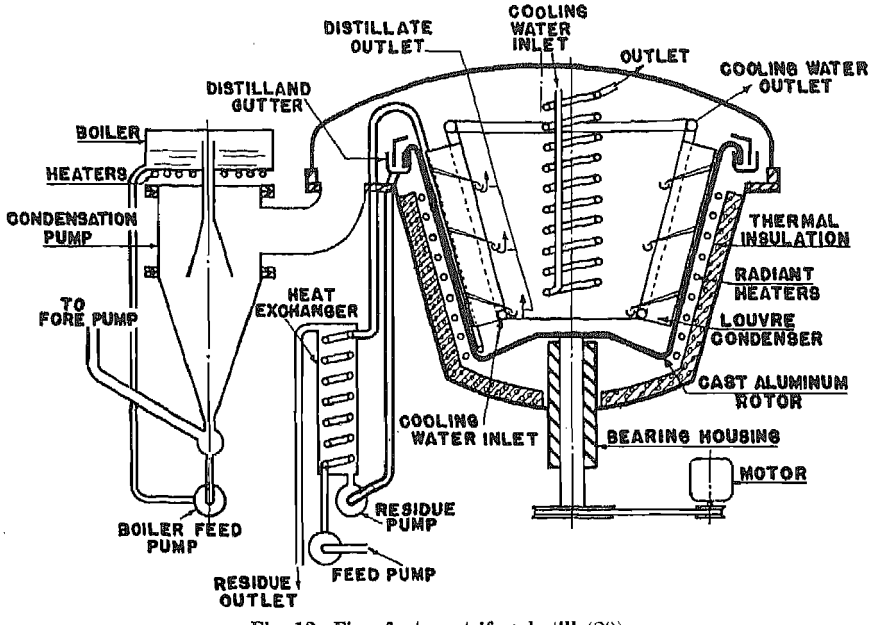


Fig. 12. Five-foot centrifugal still (20).

Figure 12 shows a typical commercial molecular still of the centrifugal type. The evaporator is a conical aluminum casting, with a diameter of 155 cm. at the top and 110 cm. at the bottom, which rotates at about 400 r.p.m. This rotor is heated by radiation from surrounding electrical resistance heaters which in turn are backed by a layer of reflective insulation. The distilland is fed to the bottom of the conical inside wall of the rotor through a pipe pointing in the direction of rotation and having a nozzle which projects the liquid at the peripheral speed of the rotor. The liquid is lifted up the distilling surface by the centrifugal force and forms a film about 0.05 mm. thick. The residue is flung into a gutter at the top of the still from whence it flows through a heat exchanger to a gear pump which discharges the oil at atmospheric pressure, or the residue may be fed directly from the gutter to the rotor of another still in series. In the latter case the conical rotor serves as a lift pump.

The vapors travel a short distance to a condenser, sometimes formed of vertical leaves or vanes closely spaced to form a louvre system. Each leaf is provided with three gutters to separate the condensate into top, middle, and bottom fractions. By circulating warm water through attached tubes, the temperature of the condenser is

adjusted to collect about 95% of the wanted constituents while the unwanted semicondensable constituents and permanent gases are rejected and pass through to the center of the still where a separate cold condenser collects some of the semicondensables. Other vapors are condensed on the dome and on a baffle placed at the entrance to the pumps, and the remainder pass on into the pumps.

The pumping system may consist of three or four steam ejectors in series acting as forepump for an oil vapor ejector and a diffusion pump in series. The latter pump has a speed of about 5,000 liters per second in the range from 10^{-3} to 10^{-2} mm. Hg.

The rate of feed of distilland is of the order of 500 kg. per hour. Care is taken to adjust the feed so that the upper edge of the rotor does not run dry. If complete distillation is required, 90–95% of the residue may be recirculated. A nonvolatile carrier oil may be added to the feed at about the same rate as the bleed-off until sufficient recycling residue is built up to keep the rotor wet. Other schemes for keeping the rotor wet with diminishing supply of distilland are described in reference (20).

The 5-ft. centrifugal still with unobstructed path between rotor and condenser gives separations of 0.80–0.95 theoretical molecular plates. *A theoretical molecular plate* is defined as the maximum separation achieved when the condenser is indefinitely close to the evaporator, and distilland is circulated so rapidly that the evaporating surface has substantially the same composition as the main bulk of the distilland, and the vapor molecules emerge at such a low density that there are relatively few collisions in flight. The separation of an ideal binary mixture under these conditions would be proportional to the ratio of the partial pressure divided by the square root of the molecular weight for the two constituents. The ratio of partial pressures often varies widely with the absolute rate of distillation which adds a further complication to the assessment of one theoretical molecular plate. The separation can be increased by adding a fractionating barrier between evaporator and condenser. This may take the form of a wire-mesh screen so formed that condensate drips on the rotor. Various schemes for improving separation by grouping banks of stills in cascade have been described (20,33a).

Centrifugal molecular stills are available commercially in all sizes from a 5-ft. to a 5-in. rotor. Falling-film stills formerly used for pilot-plant operations and laboratory analytical molecular distillations (42) are also available but have been largely superseded by the centrifugal still.

The decomposition hazard (21), which may be estimated by multiplying the average pressure in the still by the time of exposure, is lowest for centrifugal molecular stills, but increases with their size. The value is one or two orders of magnitude higher for falling-film stills and many thousands of times higher for column stills (22). The centrifugal still is particularly adapted for thermally unstable liquids of high viscosity and requiring temperatures of 100–280°C. for distillation in a high vacuum. It has been successfully applied to the commercial distillation of oil-soluble vitamins, sterols, animal fats, and high-molecular-weight plasticizers.

Vacuum Metallurgy. The application of vacuum techniques to metallurgy on an industrial scale is now well established and is growing rapidly (15,31). Large vacuum furnaces for melting of steel and chromium alloys were first developed by W. Rohn (39) in Germany during the years 1914–1940. Magnesium was produced by reduction of magnesite with calcium carbide in steel retorts at pressures under 1 mm. Hg in England from 1935 up to the time during World War II when Canada and the U.S. began producing magnesium from dolomite by reduction with ferro silicon at pressures

from 0.01 to 0.2 mm. Hg at a sufficient rate to alleviate the shortage (37). Barium, strontium, and calcium have been produced for several years in vacuum furnaces by reduction of the oxides with aluminum (31). The alkali metals have also been produced by vacuum methods.

Pure uranium and zirconium are produced by vacuum techniques for use in atomic energy reactors. Vacuum furnaces are required for the production of pure ductile *titanium, tantalum, molybdenum,* and special steel alloys for jet-engine parts. The electronics industry makes use of high-purity vacuum-melted copper, germanium, and silicon. Zinc is removed from lead under vacuum after desilverization. The thorough outgassing of molten steel alloys under vacuum results in greater strength, greater corrosion resistance, and longer life for bearings, springs, fine drawn wire, and similar parts in which cohesive crystal structure is desirable.

Sintering (see *Powder metallurgy*), bright annealing, heat treating, and soldering of metals may be performed in a high vacuum, or vacuum may be used before the introduction of pure hydrogen. The brazing of metals to ceramics by the titanium hydride process employs a high vacuum.

Several vacuum techniques have been developed for the analysis of impurities in metals. The vacuum fusion method for the analysis of gaseous elements and the low-pressure combustion method for the determination of carbon in metals are described in reference (8a).

Many of the problems of applying vacuum techniques to metallurgy have now been solved by the development of large pumps for the 10^{-4} to 1 mm. Hg range and the improved design of large induction-heated furnaces. However, while considerable data have been obtained (28,36) on the reactions between materials that are, or might be, used in construction of furnaces and crucibles and the vapors of metals and inorganic compounds at temperatures above 1000°C., more research is needed on the chemical behavior of materials in vacuum furnaces. Some of the special techniques that have been developed and the problems encountered are presented in the following sections.

Furnace Design. Externally heated vacuum retorts of nickel-chrome steel were used in the manufacture of magnesium by the Pidgeon process during World War II, and are still used in the production of calcium. Retorts built from iron cannot be heated above 500°C. without excessive scaling of surfaces exposed to the atmosphere. Iron sprayed with a coat of stainless steel can be used up to 700°C. Iron sheathed in Inconel can be used up to 1200°C., but above 800°C. mild steel begins to creep under moderate pressures. Above 1100°C. both mild steel and stainless steel show pronounced creeping. Although the retorts used in the Pidgeon process had walls more than 1 in. thick, they gradually became deformed. Iron retorts enclosed in a vacuum chamber can be used up to temperatures of 1200°C., but heating cannot be accomplished from the outside with gas or oil burners. A vacuum-enclosed electric resistance furnace was designed by Bagley (31) for manufacturing magnesium by the ferrosilicon process during World War II.

Fused quartz, mullite, alundum, zircon, sillimanite, and pure refractory oxides are used for small tubular retorts heated externally by electrical resistance ovens or by induction heating coils. Furnaces for melting and casting of metals use vertical crucibles of graphite, alumina, magnesia, zirconia, beryllia, or thoria enclosed in a large metal vacuum chamber. Heating is accomplished by an arc, induction coils, or resistance windings located inside the vacuum tank and operated at sufficiently low voltages

to avoid glow discharges or uncontrolled arcing. Graphite resistance heating units can be employed in vacuum furnaces operating up to 1600°C., above which carbon evaporates at a rate that may cause trouble. Silicon and aluminum vapors attack graphite heating elements or crucibles to form carbides, but graphite can be used in calcium reduction furnaces. Graphite reacts with most refractories and oxides above 1300°C. Silicon carbide resistance heating units are not recommended above 1400°C. in vacuum (12). Tungsten and molybdenum can be used for resistance heating in vacuum but tend to become brittle at high temperature. Tungsten, molybdenum, and tantalum heating units are attacked by oxygen and water vapor. Resistance heating units are always surrounded by insulation or radiation shields. Light-weight firebrick and zircon brick can be used inside vacuum furnaces (7,36).

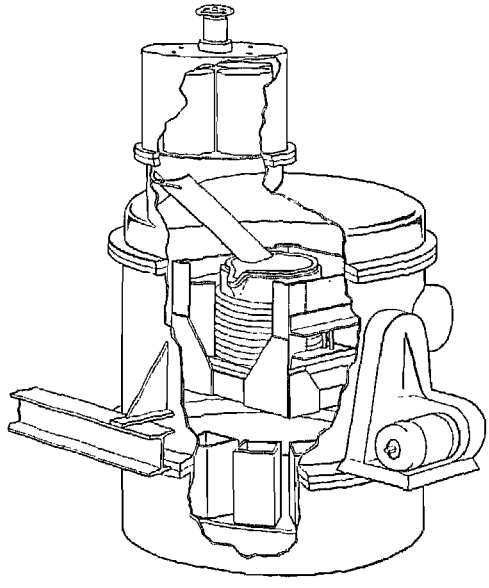


Fig. 13. Induction-heated tilt-pour furnace.

High-frequency (1–20 kc.) induction heating is used for high-temperature furnaces (1000–2000°C.). For melts up to 5 lb., a radio-frequency generator may be used. For larger melting furnaces, motor generators with frequencies of 9.6 or 3.0 kc. are employed, and for very large furnaces a frequency of 0.96 kc. is recommended. The lower frequencies give greater stirring of the melt. The power required depends on the melting time and size of the charge. For pilot-plant furnaces with melting times of about 30 minutes, approximately 1 kw. of generator capacity per pound of steel is required (34). Large furnaces for melting 1000 lb. or more of ferrous or nickel base alloys require about 0.3–0.5 kw. generator output per pound of melt for melting times of one to two hours.

Figure 13 shows a typical induction-heated furnace for melting 1000-lb. batches. The crucible is surrounded by several turns of water-cooled copper coil through which is passed the high-frequency current. The coil must be kept sufficiently far from structural metal parts of the furnace to avoid undue power losses. A coil voltage of about 200 volts is preferred to avoid arcing and glow discharge, but very large furnaces (over

200 kw.) usually employ 400 volts. The crucible assembly is mounted on trunnions or pivots for tilt pouring. In small furnaces flexible leads may be connected to the coil so that the crucible can be tilted. In early pilot-plant furnaces these consisted of a braided cable run through a rubber water hose which transmitted the cooling water. Most large induction furnaces now use contact blocks against which the ends of the coil rest during melting, or the crucible assembly is mounted on a rotating seal through the furnace wall with coaxial leads passing through the seal.

Vacuum arc furnaces are used for metals with a very high melting point, such as molybdenum, or for melting metals, such as zirconium, that react with available crucible materials. The pressure must be either less than 0.05 mm. Hg or else kept above the point at which glow discharges occur by admitting an inert gas. The arc must be confined to the vaporized metal by controlling the voltage and pressure. The arc is struck between a long vertical adjustable electrode and the metal in the crucible. The movable electrode may be a consumable rod of the same metal as that being melted or it may be a water-cooled permanent electrode of graphite, tungsten, or molybdenum. In the arc melting of molybdenum a consumable electrode is continuously formed by compacting and sintering powder in a mold at the top of the furnace (41). In the melting of titanium sponge the ingot grows as the molybdenum powder, or crushed titanium sponge, flows into the hot zone at the top of the ingot which descends into a water-cooled mold (15).

Loading and Pouring. The crucible is usually filled to about two-thirds of its volume. Frequently constituents must be added to the batch under vacuum. In small furnaces, it is sometimes advisable to reduce the temperature of the crucible below the melting point since the added material may release quantities of gas causing spattering. In large furnaces, this precaution may not be necessary if the material is added slowly. The additions are usually dropped from buckets into a chute. Devices for emptying the buckets by external controls have been described by Nisbet (40). Additional ingredients may also be suspended above the crucible or chute on a wire which can be fused by an electric current.

The melt must be poured into water-cooled molds, since allowing the melt to solidify in the crucible requires a long time and usually results in large pipes and nonuniformity. The melt may be poured from a lip at the top of the crucible by tilting the crucible and heating coil or by tilting the whole furnace about a rotary sealed pumping line. The melt may be tapped from the bottom of a crucible provided with a hole sealed by a stopper rod. Or, the bottom of the crucible may have a short pipe sealed by a fusible plug which can be melted by an electric heater surrounding the pipe. Glass viewing ports are usually required so that the operation can be controlled from the outside. The glass must be protected by retractable metal shields to avoid being obscured by material volatilized and spattered from the melt.

Ceramic or sand molds outgas too much and water-cooled copper or steel molds are therefore commonly used. Casting must be done slowly to allow the liberated gas to be pumped away and to avoid long pipes. Water cooling rates approximate one gallon per minute for each pound of melt (except for metals like beryllium that produce brittle ingots if cooled too rapidly). Bottom disks of ceramic may be used to prevent excessive cooling of the first run of metal. Colloidal graphite applied to the walls of the mold and baked on will facilitate the release of the ingot from a chilled metal mold.

Chemical Reactions at Low Pressures. Inorganic chemical reactions at room temperature are very slow in high-vacuum systems because of the absence of water and

other ionizing solvents that are too volatile to remain in the condensed phase. However, at elevated temperatures reactions may occur at appreciable rates in a vacuum system. For most inorganic compounds and metals, temperatures above 800°C. are required for melting or dissociation. Above 1300°C. so many substances react that it is difficult to find materials for the structural parts of the vacuum system that will not be corroded or cause contamination. Many high-temperature reactions are facilitated by the use of low pressures because surface films of oxides and nitrides are avoided and volatile products are pumped or distilled away from the reaction mixture. For example, beryl ore reacts with aluminum or magnesium fluoride at 1000°C. in a vacuum to produce beryllium fluoride, which is evaporated in the process (31).

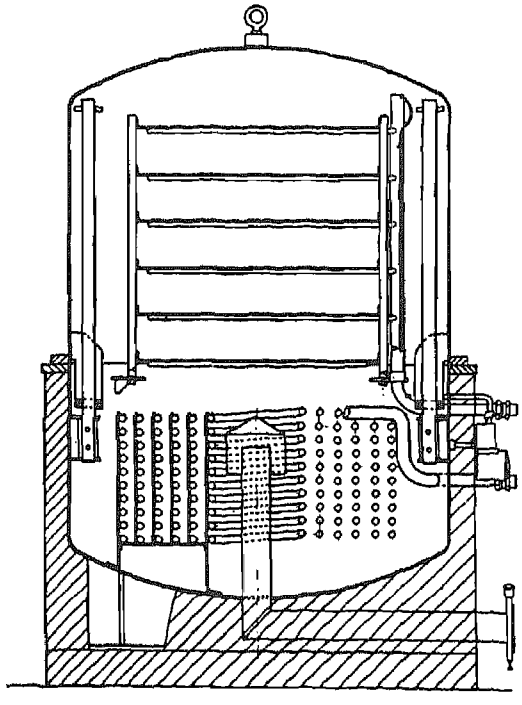


Fig. 14. Shelf dryer (17).

Reactions to be carried on in molten baths require vigorous stirring of the bath since the gaseous products can escape readily only from the surface layers. The hydrostatic pressure of the liquid a few millimeters below the surface may be greater than the partial pressure of the reaction product at the prevailing temperature. A large surface area is required for the rapid removal of volatile products. Turbulent stirring is required to keep the surface layers from becoming clogged with nonvolatile products and depleted of reactants. This suggests the desirability of using thin films or falling drops of liquid in equipment similar to that used for vacuum distillation of organic materials.

Among the reactions used in vacuum metallurgy are the following: the Pidgeon process (31) (see *Magnesium and magnesium alloys*, Vol. 8, p. 572); the Guntz process (31) (see *Alkaline earth metals*, Vol. 1, p. 460); the Kroll process (37) (see *Zirconium*); the Van Arkel process (18) (see *Zirconium*); the Van Impe process (45) (see *Uranium*).

Vacuum Dehydration. The removal of water and other solvents at pressures in the moderate-vacuum region is treated in *Distillation*, Vol. **5**, p. 184; and *Filtration*, Vol. **6**, p. 518. The application of high-vacuum techniques to drying processes will be described briefly in the following section.

The vapor pressure of ice at 0°C. is 4.6 mm. Hg, but many biological preparations are not completely frozen until the temperature is well below −17°C., at which temperature the vapor pressure of pure ice is 1.0 mm. Hg. From a theoretical viewpoint, drying of biological preparations should always be conducted at temperatures below the minimum eutectic temperature so that aggregation of molecules and concentration of salts cannot occur. In practice this is seldom possible, and the engineering criterion for safe drying temperature is that no frothing and no shrinking should occur during drying (17). For most preparations, such as blood plasma and streptomycin, this means drying at pressures in the high-vacuum region (10,17). While freeze drying (high-vacuum) techniques have been applied to dehydration of fruit juices and other foods to a very low moisture content, present practice tends toward low-vacuum methods involving absorption columns in which liquid desiccants such as 50% lithium chloride or bromide solution, are circulated (7).

The material to be dried must first be frozen on a tray or inside suitable containers with wide openings for rapid escape of water vapor. The material should preferably be frozen in a thin layer to provide maximum surface for evaporation. The design of the vacuum chamber depends on the form of the trays or containers holding the frozen material. A typical shelf dryer for trays is shown in Figure 14. Provisions should be made for warming the material to maintain adequate rate of evaporation.

The pumping system usually consists of a cold trap and an oil vapor pump backed by a mechanical pump having means for separating water from the sealing oil or operated with gas ballast. On small systems, chemical desiccants may be used. In large installations where high-pressure steam and an adequate supply of cooling water are available, a four- or five-stage steam ejector can be directly connected to the drying chamber. However, since 1 sq.in. of cold trap surface can condense water vapor at the rate of about 90 liters per second, it is in general not difficult to design cold traps that will have a "pumping speed" for water vapor equivalent to a very large vapor jet pump. The bulk of the water is therefore usually removed by a cold trap and the drying completed by a vapor jet pump while the cold trap is isolated from the drying chamber by valves and "defrosted." Trap temperatures should, in general, be below −40° C. At this temperature the vapor pressure of ice is about 0.1 mm. Hg. Mechanically refrigerated cold traps with temperatures as low as −70°C. and capable of collecting several hundred pounds of ice are available commercially. A continuously operating cold trap has been developed in which the water vapor condenses on the inside wall of a cylinder, and the ice or "snow" is scraped off by rotating blades. The ice drops into an evacuated reservoir where mechanical means are provided for ejecting the ice into the atmosphere without loss of vacuum. Large units of this type will handle up to 55 lb. of water per hour (14).

As complete dryness is approached, the temperature of the material is gradually raised to 0°C. or above to drive out the last traces of moisture. For estimating purposes it can be assumed that the ice surface of the frozen material in the vacuum chamber will recede at the rate of 0.2–1 mm. per hour (10). Residual moisture content is normally about 0.5% (2).

Bibliography

(1) Alpert, D., *J. Appl. Physics*, **24**, 860–76 (1953).

(1a) Barr, W. E., and Anhorn, V. J., *Scientific and Industrial Glassblowing and Laboratory Techniques*, Instrument Pub. Co., Pittsburgh, Pa., 1949.

(2) Beckett, L. G., *J. Sci. Instruments*, **28**, Suppl. No. 1, 66 (1951).

(3) Behar, M. F. (ed.), *The Handbook of Measurement and Control*, Instruments Pub. Co., Pittsburgh, Pa., 1951, ch. 7.

(4) Blears, J., and Leck, J., *Brit. J. Applied Phys.*, **2**, 227–32 (1951).

(5) Clausing, P., *Ann. Physik*, **12**, 961–89 (1932).

(6) Cook, L., "Vacuum Properties of Plastic Materials," *U.S. A.E.C. Document*, MDDC-588 (Tech. Inform Div., Oak Ridge, Tenn.), 1947.

(7) Davy, J. R., *Industrial High Vacuum*, Pitman and Sons, London, 1951.

(8) Dayton, B. B., *Ind. Eng. Chem.*, **40**, 795–803 (1948).

(8a) Dayton, B. B., "Vacuum Technique and Analysis," in Berl, W. G. (ed.), *Physical Methods in Chemical Analysis*, Academic Press, N.Y., 1951, Vol. II.

(9) Dushman, S., *Scientific Foundations of Vacuum Technique*, Wiley, N.Y., 1949. Figure 6 courtesy John Wiley & Sons, Inc.

(10) Flosdorf, E. W., *Freeze-Drying*, Reinhold, N.Y., 1949.

(11) Fondrk, V. V., *Chem. Eng. Progress*, **49**, 3 (1953).

(12) Fox, K., Stauffer, R. A., and DiPietro, W. O., *Iron Age*, **161**, No. 9, 78–84 (1948).

(13) Gerow, G. P., *Iron Age*, **173**, No. 7, 142–44 (1954).

(14) Goddard, D. R., *J. Sci. Instruments*, **28**, Suppl. No. 1, 43 (1951).

(15) Gray, A. G., *Steel*, **132**, 88–91 (1953).

(16) Guthrie, A., and Wakerling, R. K., *Vacuum Equipment and Techniques*, McGraw-Hill, N.Y., 1949. Figure 11(a) courtesy Atomic Energy Commission and McGraw-Hill Book Company, Inc.

(17) Harris, R. J. C. (ed.), *Biological Applications of Freezing and Drying*, Academic Press, N.Y., 1954. Figure 14 courtesy Academic Press.

(18) Hayes, E. T., and Stephens, W. W., *Metal Progress*, **63**, No. 5, 97 (1953).

(19) Hickman, K. C. D., *J. Appl. Phys.*, **11**, 303–13 (1940).

(20) Hickman, K. C. D., *Ind. Eng. Chem.*, **39**, 686 (1947).

(21) Hickman, K. C. D., and Embree, N. D., *Ind. Eng. Chem.*, **40**, 135 (1948).

(22) Hickman, K. C. D., *Ind. Eng. Chem.*, **40**, 16 (1948).

(23) Hogg, B. G., and Duckworth, H. E., *Rev. Sci. Instruments*, **19**, 331 (1948).

(24) Holland-Merten, E., *Handbuch der Vacuum Technik*, Wilhelm Knapp, Halle, 1950.

(25) Jackson, D. H., *Chem. Eng. Progress*, **44**, 347–52 (1948).

(26) Jacobs, R. B., and Zuhr, H. F., *J. Appl. Phys.*, **18**, 34 (1947).

(27) Jaeckel, R., *Kleinste Drücke, ihre Messung und Erzeugung*, Springer, Berlin, 1950, pp. 111–17.

(28) Johnson, P. D., *J. Am. Ceram. Soc.*, **33**, 168–71 (1950).

(29) Knoll, M., Ollendorff, F., and Rompe, R., *Gasentladungs-Tabellen*, Springer, Berlin, 1935, p. 145.

(30) Kohl, W. H., *Materials Technology for Electron Tubes*, Reinhold, N.Y., 1951.

(31) Kroll, W. J., *Vacuum*, **1**, 163–84 (1951).

(32) Latham, D., Power, B. D., and Dennis, N. T., *Vacuum*, **1**, 97–114 (1951); **2**, 33–49 (1952).

(33) Lawrance, R. B., *Chem. Eng. Progress*, **50**, 155 (1954).

(33a) Madorsky, S. L., *J. Research Natl. Bur. Standards*, **44**, 135 (1950).

(34) Malcolm, E. D., *J. Sci. Instruments*, **28**, Suppl. No. 1, 63 (1951).

(35) Messina, P., Brown, J. J., and Bohnlofink, J., *Chem. Eng.*, **61**, 161 (1954).

(36) Michaelson, H. B., *Materials and Methods*, **38**, No. 6, 110–14 (1953).

(37) Miller, G. L., *Vacuum*, **11**, 19–32 (1952).

(38) Morse, R. S., *Rev. Sci. Instruments*, **11**, 272–81 (1940).

(39) Motock, G. T., *Iron Age*, **158**, No. 24, 64 (1946).

(40) Nisbet, J. D., *Iron Age*, **159**, No. 25, 56–59 (1947); **161**, No. 12, 79 (1948).

(41) Parke, R. M., and Ham, J. L., *Metals Technology* (Am. Inst. Min. Met. Eng.), **13**, TP No. 2052 (1946).

(42) Perry, E. S., and Hecker, J. C., "Distillation Under High Vacuum," in Weissberger, *Technique of Organic Chemistry*, Interscience, N.Y.-London, 1951, Vol. IV, pp. 495–602.

(43) Reimann, A. L., *Vacuum Technique*, Chapman & Hall, London, 1952.

(43a) Riegel, E. R., *Chemical Process Machinery*, Reinhold, N.Y., 1953.
(44) Romand, J., Schwetzoff, V., and Vodar, B., *Le Vide*, **6**, 1046 (1951).
(45) Van Impe, J., *Chem. Eng. Progress*, **50**, 230–34 (1954).
(46) White, W. C., and Hickey, J. S., *Electronics*, **21**, 100 (1948).
(47) Zabel, R. M., *Rev. Sci. Instruments*, **4**, 233 (1933).

B. B. DAYTON

VACUUM TUBES

Essentially a vacuum tube consists of (*a*) the cathode, which is the source of electrons, (*b*) one or more grids which control the flow of electrons and the operation of the tube, and (*c*) the anode or plate. The operation of vacuum tubes is discussed under *Electronics* (Vol. **5**, p. 558).

Theory of Electron Emission

In metals in the solid state, the metallic bond, which is responsible for the cohesion of metals and gives rise to the crystal structures characteristic of metals, is nondirectional; *i.e.*, the atomic or molecular forces are exerted in all directions within the body of the crystal, chiefly upon the immediately neighboring atoms. According to modern concepts the metal lattice consists of close-packed positive metal ions with free electrons moving in the interstices of the lattice. These valence electrons move from one atom to another in random motion with thermal velocities. In the presence of an externally applied potential difference the electrons acquire an additional velocity in the direction of and proportional to the field, thus accounting for the high electrical conductivity of metals.

At normal room temperatures these free electrons do not escape from the body of the metal. This is evident from the fact that a metal does not become positively charged after standing at room temperatures for any length of time. According to the theory of behavior of free electrons, the reason for the failure of electrons to escape is the existence of a potential energy barrier at the boundary or surface of the metal. This barrier occurs because of the lack of symmetry in the arrangement of charges about the positively charged nuclei at the boundary. An electron inside the body of the metal is surrounded symmetrically and in general experiences no net force in any direction. On the other hand, an electron starting through the surface has only positive forces pulling it back to the metal and none pulling it out. In order to escape from the surface of the metal an electron must have kinetic energy equal to or greater than the potential gradient at the barrier. The property of a metal called "work function" is a measure of the amount of kinetic energy that is capable of ejecting an electron from the metal. The greater the work function of a metal, the larger is the amount of kinetic energy required to release an electron from the metal.

The flow of electrons from metals may be obtained in a number of ways, namely, by thermionic emission, by photoelectric emission, by secondary emission, or by field emission.

Thermionic Emission. If the temperature of a metal is increased sufficiently, some electrons will obtain enough kinetic energy to enable them to surmount the potential energy barrier and escape from the surface of the metal. This is known as thermionic emission. All solids will emit electrons as a result of applied thermal energy, such emission depending upon the temperature of the material and its constitution. The electron current emitted from a cathode is described by Richardson's equation as it has been modified by Dushman:

$$I = AT^2 \exp\{-e\phi/KT\}$$

where I is the current emitted in amp./cm.^{2}, A is an emission constant expressed in amp./(cm.^{2})(deg.^{2}); T is absolute temperature in degrees Kelvin; e is the electron charge of 1.6×10^{-19} e.s.u.; K is Boltzmann's constant; and ϕ is the work function of the material expressed in volts. We can see that at any given temperature and area of a cathode the emission depends upon the work function of the metal and the value of A which is theoretically equal to 120 for pure metals. The greater the work function, the lower will be the emission at any given temperature. In order to compensate for a high work function the operating temperature of the cathode may be increased, but this will in-

crease the rate at which the emitter evaporates and will decrease the life of the cathode correspondingly.

Photoelectric Emission. Many materials may emit electrons when light or radiation of a suitable wave length impinges on the surface. This form of electron emission is known as photoelectric emission, and some metals whose surfaces have been specially treated are very efficient emitters. They form the basis of phototubes, which detect and measure light, and ultraviolet or infrared radiation. See *Photoelectric cells*.

Secondary Emission. When electrons or ions strike a metal surface from outside, electrons will be emitted from the surface of the metal. In this case the electrons obtain sufficient energy for emission from the incident electrons. This bombardment by the incident electrons may change the characteristics of some surfaces.

Field Emission. Field emission differs from the preceding three types of emission in that energy is not given to the electrons in the metal. Instead, the electrodes and applied potentials are so arranged that an intense electric field is produced at the emitting surface. This electric field modifies the confining potential energy barrier to such an extent that electrons may penetrate it and escape. The positively charged electrode may actually be considered as pulling the electrons out of the surface of the metal.

Cathode Materials

Tungsten. The most common source of electrons in transmitting and high-power tubes is tungsten, mainly because it can be raised to a higher temperature without melting than any other metal. It has a comparatively high work function of about

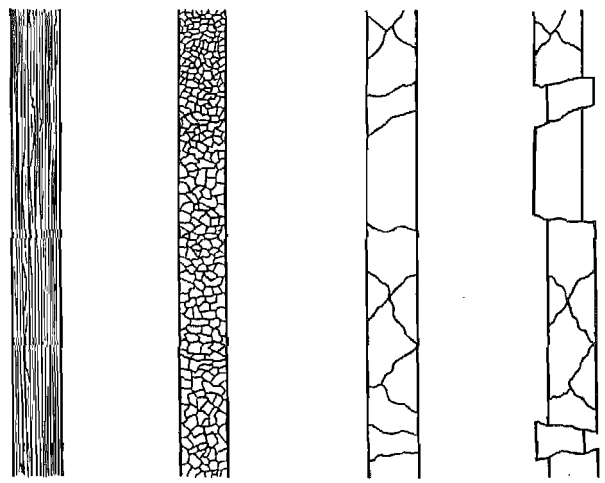


Fig. 1(*a-d*). Changes in structure of pure tungsten filaments heated by alternating current (5).

4.5 e.v. and consequently has relatively low emission. Its emission efficiency, *i.e.*, its ratio of emitted current to power radiated, is very low. This makes tungsten an expensive source of electrons because of the amount of power required. For these reasons tungsten is not used as an emitter unless the application is such that other emitters cannot be used.

Tungsten has its greatest application in high-voltage x-ray and power tubes where plate potentials operate above 3000–4000 volts, because tungsten is not subject to loss of emitting properties as a result of positive-ion bombardment at these high potentials. These positive ions occur in a tube because of the small amount of residual gas

always remaining in commercial vacuum tubes. In high-voltage tubes these positive ions have their greatest energy and bombardment is so severe that the emitting properties of other materials are impaired to the extent that they cannot be used. Like other materials, tungsten is subject to reduction of emission by poisoning from contamination by some gases, but it cleans up more readily by heating or bombardment than other materials. The life of a tungsten filament is considered at the end point after its diameter has been reduced by 10% because of evaporation. Hot spots form and lead to burnout of the filament at these points.

Pure tungsten wire has a fibrous structure, but at temperatures above 1000°C. it loses this structure and crystal grains begin to grow (Fig. 1). The size of these grains depends upon the temperature and the time of heating. The crystal size may grow to the point where it extends across the full wire diameter, and slippage may then occur along the grain boundaries at right angles to the axis of the wire. This is known as offsetting and leads to hot spots and burnouts. This excessive crystal growth can be prevented by the admixture of thorium oxide to the tungsten powder batch from which the wire is made.

Thoriated Tungsten. Thoriated tungsten usually contains 1–2% thoria (ThO_2). During the exhaust cycle in the manufacture of tubes the thoriated filament is heated to above 2500°C. for 1 minute. The thoria decomposes to pure thorium and oxygen, and the oxygen is pumped out of the tube. The temperature of the filament is then held at about 2100°C. for a few minutes, during which time the thorium diffuses to the surface of the filament more rapidly than it evaporates, thus building up a thin layer of thorium on the surface. Thorium has a lower rate of evaporation from tungsten than it has from itself at a given temperature; therefore, a thin layer of thorium may remain on the surface of hot tungsten at temperatures that would cause rapid evaporation from pure thorium. The work function of thoriated tungsten, of about 2.8 e.v., is also lower than that of either pure tungsten or thorium, thus giving higher emission than either at any temperature where the thorium still remains.

Thoriated tungsten filaments are usually carburized by heating to about 1700–1800°C. in a hydrocarbon vapor until the resistance of the filament increases by 10–20%. This allows the reduction of thoria to thorium at a lower temperature and is necessary if the filament is to withstand appreciable positive ion bombardment, by which thoriated tungsten filaments are susceptible to deactivation. This carburization increases the life of the filament because the evaporation of thorium from a carburized surface is several times smaller than from a pure tungsten surface.

The disadvantages of thoriated tungsten are that it is limited to operation at relatively low-voltage gradients compared to tungsten because of sputtering of the surface film of thorium by gas ions, and it is difficult to work mechanically. Fabrication of a large-area cathode is almost impossible, and it is generally restricted to wire or small-diameter rod form.

Tantalum. Tantalum is the only other pure metal emitter that is efficient at elevated temperatures. Although it cannot be heated to as high temperatures as tungsten, its work function is lower, 4.1 e.v. compared to 4.5 for tungsten. At a given temperature its emission may be up to ten times that of tungsten, but its rate of evaporation is also much higher. If both are operated at temperatures which will give the same emission, the life of the tantalum filament will be shorter. The great advantage of tantalum over tungsten is that tantalum can be drawn and formed to almost any

shape required regardless of size. A disadvantage is that it is contaminated easily by residual gases in the tube.

Oxide-Coated Cathodes. The most economical source of electrons for most commercially produced electron tubes today is the oxide-coated cathode. Among the electron tubes currently produced that utilize oxide-coated cathodes are radio receiving tubes, television tubes, cathode ray tubes, magnetrons, klystrons, and traveling wave tubes.

It was found, as early as 1904 by Wehnelt, that copious electron emission could be obtained from alkaline-earth oxide coatings on a basis metal of platinum. Barium, strontium, and calcium oxides are all used today. The amounts of each of these are variable, but the optimum ratios vary between 60 and 70% strontium oxide and 40 and 30% barium oxide for "double oxides" and about 47% barium oxide, 43% strontium oxide, and 10% calcium oxide for "triple oxides." Such coatings will give high emission at low temperatures with high efficiency. At about 800°C. an oxide-coated cathode will give about the same emission as a tungsten filament operating at 2000°C., but will be operating at an efficiency 20 times higher. The work function of oxide-coated cathodes is about 1.2 e.v. compared to 4.5 for tungsten.

There are conflicting theories concerning emission from oxide cathodes, but it is generally conceded that a thin layer of barium metal is formed on the surface and in the interstices of the oxide, and that emission takes place from the excess metal on the surface. It is the complex structure of the surface that is effective in reducing the potential energy barrier and therefore the work function. The excess barium is obtained from the barium oxide by chemical reaction with the core or basis metal, by electrolytic reduction by the potential energy gradient through the oxide coating, and by reduction by positive-ion bombardment.

The basis metal has a decided influence on the emission from the oxide cathode, and metals such as titanium, tantalum, nickel, and molybdenum may be used. The most commonly used core metal today is nickel, mainly because of its desirable physical properties and low cost. Pure nickel is believed to have no appreciable reducing effect on the oxide, and it is therefore common practice to add reducing agents to the nickel melt to obtain a slight amount of reduction of the oxide coating to free barium for high electron emission.

Excessive amounts of reducing agents may reduce too much oxide, thus shortening the life of the cathode. In certain tubes, such as power output pentodes and other tubes with close cathode to grid spacing, and for vacuum tubes with high cathode operating temperatures, a passive nickel with reducing agents excluded is used. Such a material is "499 nickel." On the other hand, when large amounts of cathode poisons are apt to be released from the tube parts and glass wall, an active cathode alloy such as "225 nickel" is used; this has a silicon content of 0.15–0.25% which gives it a strong reducing effect. Among other alloys used are "220 nickel," which is fairly easily activated without liberation of excessive amounts of free barium. It is a normal cathode material with the silicon and magnesium content restricted to 0.01–0.05 and 0.01–0.10% respectively.

Other reducing agents which may be used in place of or in addition to silicon are titanium, aluminum, magnesium, and carbon. When carbon is used, the reduction reaction produces volatile products which are pumped out of the tube during exhaust or cleaned up by getter action. The other reducing agents form compounds such as

barium silicate, barium titanate, barium aluminate, and magnesium oxide at the surface of the nickel. These compounds form an interface layer between the basis metal and the oxides which may, if the layer is too heavy, have harmful effects on the operation of the cathode, such as a lowering of cathode temperature, resulting in lower emission, high resistance in the cathode circuit, and poor bonding between the oxide and the basis metal which results in sparking and peeling of the coating.

In preparing conventional oxide-coated cathodes, since the alkaline-earth oxides react with moisture in air, the coating is generally applied to the cathode as a mixture of carbonates. During evacuation of the tube the cathode is heated to 900–1200°C. to decompose the carbonates to the oxides. The carbon dioxide released is pumped out of the tube during the evacuation. Thermal reduction also occurs with some evaporation of liberated metal. Sometimes full emission is obtained immediately after sealing in of the tube, but usually the cathode must be activated. This is done by making the cathode negative with respect to the other elements in the tube and applying a potential of 100–200 volts over a period of time during which the cathode is operated at about 700–800°C. After the electrolysis and positive-ion bombardment have built up the emission to a stable value, the filament or cathode is ready to use.

Oxide-coated cathodes have a tendency to deactivate under positive-ion bombardment during operation of the vacuum tube, and, although they are more rugged than thoriated tungsten in this respect, they are normally used in tubes with low plate voltage. They are also very susceptible to poisoning and emission decay when exposed to such gases as oxygen, sulfur, and chlorine and other materials.

Another advantage of oxide-coated cathodes is that they may be heated indirectly, and therefore cathodes at different potentials may be heated from the same source. Also an advantage for many applications is the fact that all electrons emerge from the cathode at the same potential with respect to the other electrodes in the tube.

Matrix and Mesh Cathodes. Successful attempts have been made to produce long-life cathodes of high emission yield by embedding the carbonate coating in a porous basis metal or wire mesh from which the free barium continues to diffuse to the surface throughout the life of the tube. In another version, carbonates are mixed with a coarse nickel powder to form a paste which is then pressed and sintered onto a recessed nickel sleeve.

Dispenser or L Cathode (4). The Philips Laboratories at Eindhoven, Holland, have announced the so-called L cathode, a dispenser type which combines many of the desirable characteristics for cathodes used in high-voltage, high-frequency vacuum tubes. A pressed tablet or cylinder of a barium-strontium carbonate mixture is held by a molybdenum base and enclosed by porous tungsten. During the evacuation of the tube the carbonates are decomposed at about 1100°C., after which the barium-strontium oxides are reduced at 1270°C. At this temperature the alkaline-earth metals and barium oxide have a very high vapor pressure, so they enter into the pores of the tungsten to form a monatomic layer of barium and barium oxide over the inner and outer surfaces. According to the Philips scientists this gives the cathode a higher yield of electrons.

L cathodes operate in a higher temperature range than conventional oxide cathodes, 900–1350°C. as compared to 700–900°C. They will withstand heavy electron and positive-ion bombardment and are more resistant to sparking than conventional oxide cathodes. They are also mechanically stable and can be manufactured to close tolerances.

Manufacture

Basically, the manufacture of vacuum tubes consists of the fabrication of the parts and their assembly into the finished product. With advances in electronics and the increase in number of types of vacuum tubes from the elementary diodes and triodes to present-day magnetrons, klystrons, traveling wave tubes, and others, the technology of vacuum tubes has advanced to an intensely intricate process in which rigid inspection and control of all raw materials and manufacturing are necessities.

Among the controls and operations which are essential in vacuum tube manufacture are: (*a*) mechanical inspection and chemical analysis of incoming materials; (*b*) chemical cleaning and electrochemical operations; (*c*) high-temperature firing in controlled atmospheres or in a vacuum; (*d*) brazing operations; (*e*) control inspections including possible spectrographic and x-ray inspections.

Some of the rigid control of materials is carried on by the manufacture of raw materials, particularly in the chemical and metallurgical industries. Purity of cathode materials, for instance, is of extreme importance in obtaining uniform end results in the finished tube. Each batch of cathode nickel is put through a series of rigid chemical and electronic tests; in fact, actual cathodes are made up and tested for emission characteristics before the batch of nickel is approved for cathode material. Likewise the manufacturer of the alkaline-earth carbonates must control his processes to give purity and uniformity of end product of various formulations, since the proper formulation of the coating suspensions, the correct choice of suspending medium, binders, and solvents, as well as the exact composition of the carbonates, are highly important. The proper choice of material is dependent upon the cathode requirements of the various types of vacuum tubes, and the crystal structure, composition, and particle size of the carbonates have to be varied to meet the cathode specifications. The carbonates are manufactured by the coprecipitation of the double or triple carbonates from a solution of the nitrates either by sodium carbonate or ammonium carbonate. The precipitation is carried out under carefully controlled conditions to give the desired particle size and crystal structure. A needle-like structure is obtained by using sodium carbonate, and a spherulitic structure by using ammonium carbonate. Only those lots which meet a high standard are used, and they, in turn, are blended to obtain maximum uniformity of end product.

Among all other raw materials whose manufacture must be carefully controlled are those materials which either make up the vacuum envelope (glass, metal, ceramic) or those which make up the components of the tube and are enclosed within the vacuum envelope.

Fabrication of the components which go into the make-up of vacuum tubes may be carried on by either the tube manufacturer or outside manufacturers. In either case the manufacturers' specifications as to materials and types of lubricating oils or drawing compounds which may be used must be closely adhered to. For example, sulfonated oils and greases are taboo in a vacuum tube machine shop because of the deleterious effect sulfur has on cathode emission. Any slight amount of sulfur that might be carried into the finished vacuum tube by being embedded in the surface of the metal parts would cause emission decay and shorten the life of the tube.

CHEMICAL PROCESSING

After the fabricated parts have been inspected, they go through chemical cleaning operations, the first step of which is degreasing in either hot liquid and/or vapor de-

greasers which utilize either trichloroethylene or perchloroethylene (tetrachloroethylene) as the degreasing material. This may be followed by a cleaning in a hot alkaline cleaner to remove any remaining traces of grease or oil.

In some cases, this degreasing, followed by a hydrogen firing of the parts, may be the only cleaning that is necessary before assembly. Usually, however, the cleaning carried on at this point is more elaborate. The purpose of this chemical processing is twofold: (*1*) to remove all greases, oxides, and other contamination and render the parts scrupulously clean before they go into the vacuum tube; (*2*) to condition the surface for further operations by etching, chemical polishing or electropolishing, by electroplating, or by a combination of these.

Copper. To remove heavy oxides from copper the usual procedure is to immerse the part in hot 50% hydrochloric acid which contains a commercial inhibitor until the oxide has been removed. Other procedures involve the use of 10% sulfuric acid or a saturated solution of ammonium carbonate usually followed by a dip in sulfochromic acid (a solution containing sulfuric acid and chromic acid, CrO_3, similar to laboratory glass-cleaning solutions, but containing a lower percentage of sulfuric acid and more water). If the amount of oxide is light, a rinse in 10% sodium cyanide may be enough to clean the part. In all cleaning operations the chemical treatment is followed by a thorough rinsing in both tap water and either distilled or demineralized water before drying. Usually the drying operation is facilitated by a rinse in clean alcohol before drying with a warm air blower or in an oven.

A bright finish may be obtained by dipping the part in a copper bright dip for a few seconds, followed by immediate rinsing. This is repeated until the desired finish is obtained. The copper bright dip is a solution of sulfuric and nitric acids in a ratio which varies between 2:1 and 6:1 in a small amount of water. The mixture also contains about ½% of hydrochloric acid.

Iron, Steel, and Kovar. All three of these metals are cleaned in hot 50% inhibited hydrochloric acid to remove any traces of oxide. Kovar, which is an alloy containing 29% nickel, 17% cobalt, 53.7% iron, and 0.3% manganese, is used for making vacuum-tight glass-to-metal seals. In addition to the aforementioned cleaning procedure Kovar may be bright-dipped in a solution similar to the copper bright dip or in a solution containing 75% acetic acid and 25% nitric acid with a little hydrochloric acid added.

Nickel. Most nickel parts may be cleaned in the same manner as iron or steel and may be bright-dipped if desired in the 3:1 acetic to nitric acid bright dip mentioned above.

Cathode nickel is treated differently, depending on the type of surface desired. Some of these cleanings are as follows:

(*1*) The nickel is degreased in acetone and boiled in a solution containing sodium carbonate, 40 g./l.; sodium hydroxide, 13 g./l.; and sodium cyanide, 13 g./l. After boiling in distilled water it is rinsed in warm 5% acetic acid and then boiled a few more times in distilled water.

(*2*) After degreasing, the nickel is etched in warm 20% nitric acid until a mouse-gray matte surface is obtained. This is followed by a distilled water rinse, and then the nickel is boiled in 50% acetic acid for 5 minutes. The cathodes are then boiled in several fresh changes of distilled water.

(*3*) If a polished surface is desired, the nickel is electropolished in a 50–75% solution of sulfuric acid. A nickel or steel cathode may be used and the work is connected

as the anode. The current density used is high enough to cause vigorous gassing at the anode. Care must be taken to keep the solution cool or it will tend to etch the work instead of polish it. The parts are rinsed thoroughly and boiled in distilled water as in the preceding two processes.

After cleaning, the nickel cathodes are fired in a hydrogen atmosphere at about 800°C. for 5–10 minutes before coating with the emission coating. In some cases the cathodes are fired in a vacuum in addition to or instead of the hydrogen firing.

Tungsten. Tungsten may be cleaned in a 20% solution of sodium or potassium hydroxide by boiling it in this solution for 5–10 minutes. If the tungsten is heavily oxidized, it may be cleaned by electrolyzing it in this solution, using an alternating current at a potential between 10 and 20 volts and a carbon electrode. If a polished surface is desired, the tungsten is electrolyzed in a solution containing 10% sodium nitrite and 10% sodium hydroxide in water.

Molybdenum. Molybdenum may be cleaned in the same way as tungsten, except that after electrolyzing it is treated with warm 50% hydrochloric acid. It may also be cleaned in nitric or sulfochromic acid solutions if the oxide is not heavy. If an etched surface is desired, the molybdenum is dipped in a solution containing 40% nitric acid, 40% sulfuric acid, and 20% water for a few seconds. The reaction is rapid and care must be exercised to keep too much metal from dissolving.

The above discussion covers some of the cleaning procedures for the common metals used in the vacuum tube industry. Among other materials which have to be cleaned are silver brazing alloys and copper-gold brazing alloys (see *Solders*), which are usually cleaned by rinsing in a 10% solution of sodium cyanide, and glass, which is cleaned in a detergent solution and/or a chromic acid glass-cleaning solution. When special cleaning problems arise, the parts are cleaned in the appropriate solution or solvent. Fluxes on brazed or soldered parts, for instance, may be removed by either hot or boiling water or by degreasing agents, depending on the type of flux used. Sometimes it may even be necessary to scrub parts with a wire brush or steel wool.

Electroplating (*q.v.*) is used in the electronics industry not as a means of applying a decorative coating, but for the following purposes: (*1*) to aid in brazing operations; (*2*) to supply a protective surface against destructive atmospheres; (*3*) to apply a highly conductive material like copper, silver, or gold to a metal such as steel for electrical purposes in high-frequency tubes such as klystrons and magnetrons.

Information on types and composition of baths and special procedures may readily be found in the *Metal Finishing Guidebook-Directory* (5). In the vacuum tube industry the metals most used for electroplating are copper, nickel, silver, and gold.

The cleaning processes and the preparation of metal surfaces before plating are very important if proper adhesion and a good plate are to be obtained. It is also important to rinse the parts thoroughly and dry as soon as possible after plating to prevent them from staining. A typical cycle for plating operations after the parts have been chemically cleaned is: (*1*) electrocleaning in an alkaline cleaner; (*2*) rinsing in hot water; (*3*) pickling in 5% sulfuric or hydrochloric acid; (*4*) in plating nickel the part may be placed directly into the nickel strike bath for a strike and then into the plating bath for plating. In plating copper, silver, or gold in cyanide baths the parts are thoroughly rinsed and then immersed in a 5–10% sodium cyanide solution for about 15 seconds, after which they are placed in the strike bath and then the plating bath. (*5*) After plating, the parts are rinsed thoroughly and dried.

Parts that go into the vacuum envelope or undergo brazing operations are usually

outgassed by hydrogen firing before and after electroplating to prevent occluded gases from blistering the plate during these operations. Stainless steel parts that are to undergo brazing operations are plated with nickel to prevent the chromium in the steel from oxidizing at the surface during the brazing.

Another important operation that may be considered part of the chemical processing operations is the **coating** of cathodes and heaters. After the cathodes have been cleaned as described previously, they must be coated to the proper thickness and density with the emitter coating. This operation must be carefully controlled to prevent contamination by foreign materials and to obtain uniform results at all times. The coating may be applied by spraying, as is usually done with indirectly heated and especially shaped cathodes, by cataphoresis in the case of filamentary-type cathodes, or by drag "process," which consists in pulling the filament wire through the cathode coating suspension until the desired thickness is obtained.

In coating filaments or heaters by cataphoresis (see *Electrophoretic deposition*, Vol. **5**, p. 608) the carbonates are suspended in a liquid medium containing a binder. The choice of liquid and binder varies among the electronic companies, some preferring inorganic solutions of high conductivity, others preferring organic solutions of low conductivity. In either case the carbonate particles become positively or negatively charged, depending upon the solution used. The coating process itself is analogous to electroplating except that we are dealing with charged suspended particles instead of ions. If the carbonates are positively charged, the cathode or filament is held in the suspension and a negative potential is applied to it. The carbonates are attracted to the filament, the thickness of the coating depending upon magnitude and duration of the applied voltage. After removal from the suspension the binder holds the closely packed coating on the filament.

Tungsten heaters are coated with a layer of aluminum oxide after cleaning usually either by spraying or by cataphoresis. After the aluminum oxide has been applied, it must be sintered onto the tungsten by firing the coated heater in a hydrogen atmosphere at 1600–1650°C.

After the component parts have been chemically cleaned, it is important that they not be handled without clean, lint-free gloves, finger cots, or tweezers when they go to the assembly line in the plant. Here they are put together with very close tolerances into assemblies and sub-assemblies. Smaller parts are usually put together by spot-welding, while the larger parts, particularly components of metal tubes, are brazed together.

BRAZING

Among the methods of brazing employed are furnace brazing, bottle brazing, induction brazing, and resistance brazing, all of which are done in a controlled atmosphere.

Furnace Brazing. The main points to be considered in furnace brazing are the design of joints, tolerance of fits, placement of the brazing material, and jigs or fixtures to hold the parts together during brazing. If the time and temperature cycles are correct, there is no reason why a clean, brazed, vacuum-tight joint cannot be obtained. A hydrogen atmosphere is used in furnace brazing to provide a reducing atmosphere that will keep the parts clean and bright during the brazing operation.

There are two requirements of a brazing alloy or solder that must be satisfied: (*1*) the solder must contain no ingredients that will vaporize (this means that solders

that contain lead, zinc, or cadmium cannot be used); (*2*) the solder must have a flow point at least 100°C. below the melting point of the metal or below the melting point of a solder used previously to join other parts of the same assembly together.

Bottle Brazing. This method is similar in principle to furnace brazing except that it may be used to apply localized heating to desired parts of the work.

Figure 2 gives a rough diagram of the type of set-up used in this operation. Hydrogen enters through a flow gage and metal tube to the top of the bell jar. A tungsten or molybdenum work coil is placed around the part of the work being brazed after the work has been mounted on a suitable platform about halfway up into the jar. Copper leads of suitable size connect the work coil to a variable voltage supply.

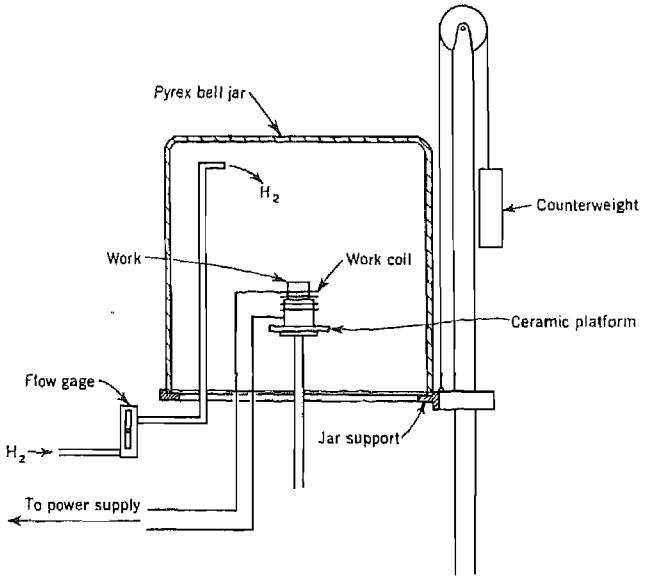


Fig. 2. Typical bottle brazing set-up.

After the jar has been completely filled with hydrogen (and all the air displaced), the current is turned on and the voltage raised slowly to the point where the work coil radiates enough heat to cause the solder to flow. When this point has been observed, the power is shut off and the work allowed to cool down enough so that it will not oxidize when exposed to air.

Induction Brazing. The set-up for induction heating is the same as in Figure 2 for bottle brazing except that the work coil consists of water-cooled copper tubing which is connected by water-cooled cables to a radio-frequency oscillator. The work coil should be as close to the work as possible without touching it to obtain maximum energy transfer. In this method it is the radio-frequency energy which with the proper coupling will induce enough heat in the work to melt the brazing material.

Vacuum firing or brazing is also realized by induction heating. Figure 3 shows a typical vacuum firing brazing set-up. The method is the same as above, the main differences being that the work is in a vacuum chamber and the work coil is outside the bell jar.

Resistance Brazing. In this method of brazing the work is placed between two graphite pieces which are machined to fit the work on both sides. A low-voltage

supply is used to pass a high current through the work to heat it to the brazing temperature. This method has special applications but is not used too extensively.

Metal-Ceramic Brazing. In recent years the use of ceramic materials in vacuum tube construction has been on the increase, and therefore various methods have been devised to braze ceramics to metals. Among the most important of these are the following.

Titanium Hydride or Zirconium Hydride Process. The ceramic is coated with the hydride and assembled with the metal part to which it is to be brazed with the brazing material. The assembly is then heated in a vacuum or inert atmosphere to the temperature where the brazing material decomposes and melts. The hydrogen evolved by the hydride is pulled out by the vacuum pumps.

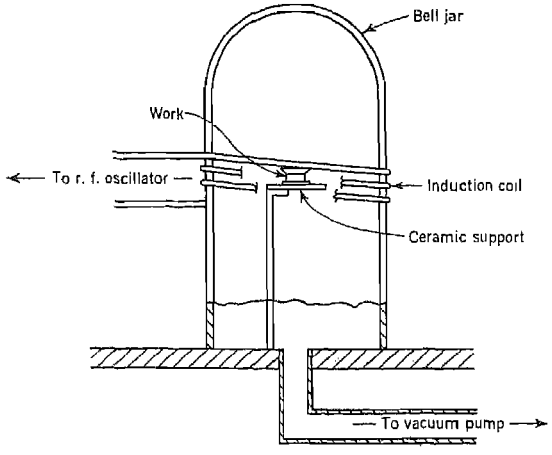


Fig. 3. Typical vacuum brazing set-up.

Active Metal Alloy Process. An active metal like titanium or zirconium may be alloyed with silver or a silver-copper solder to form a brazing material that will make a good seal between metal and ceramics.

Metal-Glass Seals. Metal-to-glass seals that are vacuum-tight have been in use from the early days of vacuum tube manufacture. The important consideration here is to have a good match between the thermal expansion characteristics of the glass and the metal. The most commonly used metals in making metal-glass seals are copper, tungsten, Kovar, and Sylvania No. 4 alloy (42% Ni, 6% Cr, 0.29% Mn, 0.04%C, 0.12% Si, balance Fe).

The glassing process must be controlled carefully if a vacuum-tight seal is to be obtained. The seal depends upon a good bond between the glass and the metal oxide layer between the glass and the metal. Usually, after cleaning, the metal is oxidized under controlled conditions to obtain an oxide that is adherent and of uniform thickness. If the part being made is a stem, the usual procedure is to place the oxidized metal parts and ground glass in a graphite mold and place this in an oven with a nitrogen atmosphere at 1050–1100°C. Other metal-glass parts are joined together on a glass lathe or in an induction brazing set-up which heats the metal to the point where the glass in contact with it melts and adheres to the metal. After the seal has been made, the part is annealed by heating to about 450°C. in an annealing oven and allowing it to cool slowly to room temperature.

TUBE PROCESSING

After all the vacuum tube components have been assembled inside the vacuum envelope, whether it be glass or metal, there are other processes which must be carried out before the tube can be considered completed.

The first process usually carried out at this stage is called *bakeout*. The tube is sealed onto the manifold of a vacuum system which is capable of pumping down the tube to the order of 10^{-7} mm. of mercury. After the tube has been pumped down to 10^{-5} mm. of mercury, the oven is heated to a temperature of about 450°C. When the oven is first heated, an increase in pressure as measured by the ion gage occurs because of the water vapor and gases being given off by the tube parts and the vacuum envelope. The bakeout continues until the pressure again drops to 10^{-5} mm. or less, at which time the oven is turned off and the tube allowed to cool down slowly in the oven. On cooling the pressure in the system will continue to drop and should reach approximately 10^{-7} mm. by the time the temperature of the oven has reached 100°C.

The next step in the processing is *bombardment*, during which the desired elements in the tube are heated to about 800°C. under vacuum to drive off any gas that may still be contained in them. This heating is usually carried out by induction heating, sometimes by electron bombardment. Electron bombardment is less severe and is limited to areas which can be heated by electron emission. In tubes using oxide-coated cathodes, pressure must be kept low to prevent bombardment of the cathode itself.

After bombardment by induction heating, the cathode is *activated*, the method depending upon the type cathode being used. In the activation of thoriated tungsten the filament is heated to 2100–2200°C. for 10–30 seconds, after which it is lowered to the normal operating point of about 1700°C. The filament is then carburized by injecting a sufficient amount of a hydrocarbon gas into the system. The temperature is raised to about 1900°C. for 1–2 minutes and the gas is then pumped out.

In the activation of oxide-coated cathodes the control of cathode temperature is very important. In case the cathode is visible, an optical pyrometer may be used to determine the temperature; otherwise cathode temperature must previously be determined as a function of power input to the filament. The activation is carried out in two steps.

(*1*) *Removal of binder.* The filament current is raised slowly until the cathode is at about 600°C., which is just below red heat. This temperature is maintained, while keeping the pressure below 10^{-5} mm., until the binder has been removed. The binder is usually a nitrocellulose lacquer, and during this process it is burned off mainly as carbon dioxide and carbon monoxide.

(*2*) *Decomposition of carbonates to oxides.* While the pressure is held below 10^{-4} mm., the filament current is raised slowly until the surface of the cathode reaches a temperature of about 1000°C. At this temperature the carbonates break down to the oxides with a rapid increase in evolution of carbon dioxide gas. To insure complete breakdown the cathode temperature may be raised to about 1100°C. for very short periods of time. Once this point has been reached, a decrease in pressure will occur when the temperature is dropped to the normal operating range of 800–900°C. A d.c. voltage may then be applied to the anode and a small amount of current drawn until the pressure drops to about 10^{-7} mm.

Another method of activating the cathode after the removal of the binder is to

raise the cathode temperature quickly to 1000°C. for one to two minutes, during which time the pressure should rise to peak and then begin to fall. The faster the activation can be accomplished, the greater the chances of getting a good emitter.

After activation of the cathode residual gases are cleaned out by electron bombardment (described above) and the tube is gettered just before sealing or tipping-off.

Gettering. The *gettering* process may be described as a chemical clean-up process which makes use of certain chemically active metals to remove residual gases in a vacuum system. These metals are known as getters and either have the ability to combine chemically with the residual gases in the tube or to absorb these gases without a chemical reaction taking place. Although it is possible to obtain pressures sufficiently low for the operation of vacuum tubes without using getters, the gettering process permits a reduction in the time required for exhausting the tube and also maintains the degree of vacuum in the sealed-off tube at the level necessary for efficient operation and long life.

The mechanism by which gases are cleaned up by a getter is quite complex. In some cases, such as with barium, the getter reacts chemically with the residual oxygen, hydrogen, nitrogen, and other gases as a result of collision between the barium atoms and the gas molecules when the barium is evaporated, and by adsorption and diffusion of the gas molecules into the metal deposited after the getter has been evaporated or flashed. The first case, in which clean-up takes place while the getter is being flashed, is called *dispersal gettering*; the second case, in which the previously flashed getter acts to clean up residual gases, is known as *contact gettering*.

Getters fall into two general classifications: flash getters and bulk getters. *Flash getters* are volatilized in the tube in the course of its manufacture. They have a dispersal gettering action and usually also some contact gettering action. *Bulk getters* are heated, but not volatilized, and they act by contact gettering only.

Flash Getters. Barium will react with or adsorb all but the inert gases, argon, xenon, helium, neon, and krypton. One of its advantages is that it will continue to adsorb gases after evaporation is completed and even after the vacuum tube has been tipped off for several days. In flash getters using barium, the barium is generally combined with aluminum, magnesium, tantalum, thorium, strontium, or calcium. Barium or barium compounds are available in metal-clad wire or pellets and after outgassing at 600–700°C. the getter is flashed at 900–1300°C. The getter is usually flashed either by induction heating or by passing enough current through it to heat it to the required temperature.

Calcium reacts in very much the same way that barium does.

Batalum is a mixture of barium and strontium carbonates coated on a tantalum wire. At 800–1100°C. the carbonates break down to the oxides which react at 1200°C. to form metallic barium.

Barium beryllate, $BaBeO_2$, is applied as a coating on tantalum wire, and has the same properties as Batalum except that it yields 40% more free barium.

Aluminum-magnesium alloy is applied as a powder painted on electrodes. It is outgassed at 400°C. and flashed between 850 and 1000°C. It absorbs gas only during the flashing, and it is used only in low-temperature applications (about 150–200°C).

Magnesium is available in the form of ribbon wire which has an outgassing temperature of 400°C. and a flashing temperature of 500–800°C. It will absorb only oxygen, nitrogen, and carbon dioxide in any appreciable amounts and is used only in low-temperature applications.

Bulk Getters. These materials generally do not react chemically with all the residual gases during gettering but have the property of being able to absorb some gases very rapidly. They come in the form of sheets, wire, or deposited powders and sometimes are used in the fabrication of electrodes in the tube. They are heated externally or are mounted on electrodes which are normally heated during the operation of the tube. Some of these are as follows:

Tantalum is used extensively in the construction of electrodes and is also available in sheet, wire, or powder form. It is degassed in high vacuum at 1600–2000°C. and has an optimum gettering temperature of about 1000°C. Tantalum will absorb 700 times its own volume of hydrogen and large amounts of oxygen and nitrogen.

Tungsten is available in the same forms as tantalum and will absorb oxygen and also some nitrogen and carbon monoxide at 1000°C.

Zirconium is available in sheets, wires, and powder, and, although it may be used in the construction of elements, it is rather expensive. It outgasses at 1000–1700°C. and has an optimum gettering temperature for hydrogen below 400°C. and for other gases between 800 and 1600°C. It is usually applied as a fine powder on anodes of transmitting tubes and heated to the required temperature by electron bombardment from the emitting filament. In some cases, zirconium hydride (see *Zirconium compounds*) is applied to the anode as a fine powder. The zirconium hydride is decomposed by heating in a vacuum so that a layer of zirconium is left on the surface of the anode to act as a getter.

Other materials which may be used are *niobium*, *thorium* applied as a powder on metal or graphite electrodes, and *thorium alloys*.

FINISHING OPERATIONS

After gettering, the tube is sealed off and removed from the vacuum pumping system. For all practical purposes the vacuum tube is completed at this point; all that remains is the application of the finishing touches. For tubes with a glass envelope the only remaining step, aside from testing, is the basing operation. This is the application of a metal or plastic cap placed over the base of the tube to protect the seal-off tip and the electrical leads coming through the glass. Adhesion of the base to the tube is accomplished by using a resin-type basing cement which is heated enough to provide the initial setting. The tube is then stamped as to type designation and is ready for shipping.

For tubes with a metal envelope, the tube must be chemically cleaned of all oxides formed during the bakeout and further processing. It is then based, painted, stamped, and shipped, provided it has passed all electrical tests.

Bibliography

(1) Dushman, S., *Vacuum Technique*, Wiley, N.Y., 1949, Chapter 10.
(2) Guthrie, A., and Wakerling, R., *Vacuum Equipment and Techniques*, McGraw-Hill, N.Y., 1949, pp. 233–34.
(3) Kohl, W., *Materials Technology for Electron Tubes*, Reinhold, N.Y., 1951.
(4) Lemmens, H., Jansen, M., and Loosjes, R., "A New Thermionic Cathode for Heavy Loads," *Philips Tech. Rev.*, **11**, 341 (1950).
(5) *Metal Finishing Guidebook-Directory*, Finishing Publications, Inc., N.Y., annual.
(6) Smithells, C., *Tungsten*, Chemical Publishing Co., N.Y., 1953, Fig. 111, p. 136, pp. 135–38.
(7) Spangenberg, K., *Vacuum Tubes*, McGraw-Hill, N.Y., 1948.
(8) Yarwood, J., *High Vacuum Techniques*, Wiley, N.Y., 1948, pp. 69–71.

J. V. FESTA

VALENCE

Today, as in the past, the term valence (or valency) has a number of different meanings. Classically it was usually regarded simply as a numerical term relating the different combining powers of the various elements, frequently expressed in terms of the number of hydrogen atoms that could combine with (or replace) one atom of the element in question (hydrogen being chosen as a reference standard since it consistently displayed a "unit" combining capacity). While this meaning is still in use, the modern tendency is to consider the way in which the individual atoms combine in a compound, that is, to consider the type of bond involved and, utilizing the concepts of the electronic theory of valence, to consider separately ionic valence, covalence, and coordinate valence (whichever type is applicable). Since these terms are uniquely defined, their use will cause less confusion than when the term valence itself is employed. Broadly speaking, the subject matter that today can properly be included in a discussion of valence will involve the whole theoretical problem of atom combination and bond formation.

According to present-day standards, a satisfactory theory of valence must be a very comprehensive one. It must explain why atoms combine at all (and why a few do not), and why the individual compounds contain definite numbers of atoms and only those numbers. The interatomic distances and the forces between atoms should be capable of being calculated theoretically, although mathematical difficulties very frequently make only approximate solutions possible. It must explain the nature of ionic and covalent compounds as well as those of an "intermediate" character. It must enable one to understand such concepts as free radicals, aromatic character, the hydrogen bond, and so forth. Finally, it should shed light on the spatial or geometric aspects of molecules, that is, why certain molecules possess a planar arrangement of atoms, others tetrahedral, octahedral, etc. Modern electronic theory, with the aid of quantum mechanics, has proved to be capable of supplying satisfactory answers to many of these questions.

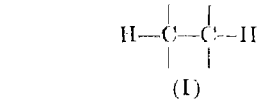
However, let us first consider the more classical meaning of valence and its usage. If an atom of a particular element is found never to combine with more than one atom of other elements, it is said to be univalent. Thus hydrogen is univalent since it forms compounds such as HX, H_2X, H_3X, . . . , H_nX, but never HX_2, HX_3, . . . , HX_n. From this it follows that any other element that combines with only one atom of hydrogen is also univalent, for example, chlorine in HCl. The terms bivalent, trivalent, tetravalent, and so forth, are used when one atom of the element combines with two, three, or four atoms of a univalent element.

Since chlorine is univalent in HCl, it is reasonable to suppose that it would be univalent in many other compounds and, therefore, that it could be used as a secondary reference for the determination of the valences of the other elements. Thus sodium in NaCl, and phosphorus in PCl_3, for example, would be assumed to be univalent and trivalent, respectively. While this assumption of a constant valence is a very valuable one, it is, of course, not always applicable. While fluorine is always univalent, this is not universally true for the other halogens, as in ClO_2, $KBrO_3$, and $NaIO_4$. The alkali metals, however, are always univalent. Some of the rare earth elements, for example lanthanum and gadolinium, are consistently trivalent in their compounds, whereas others are capable of exhibiting different valence states, although much less readily (see *Rare earth metals*). Although carbon is tetravalent in the great majority of its compounds, there are a few exceptions, as in CO, RNC, and MONC (the fulminates).

In general, it can be stated that while a few elements always exhibit a constant valence and a few very nearly always, the majority commonly display a variable valence. Nevertheless, since many of the elements in the latter class usually exhibit only a limited number of different valences, there is normally little difficulty in deciding which is operative in a particular compound. As a matter of fact, it was the assumption of constant valence (or valences) that really formed the basis for the rapid development of the structural theory in chemistry.

The actual determination of the valence of an element in a compound requires a knowledge of its molecular formula, obtained from its percentage composition and molecular weight. However, the information contained in a molecular formula frequently is not sufficient. Thus, while oxygen is obviously bivalent in H_2O, it might appear to be univalent in H_2O_2 since there is only one hydrogen atom for each oxygen atom. Nevertheless, a satisfactory structural formula can be written with the assumption that oxygen remains bivalent in the compound, namely H—O—O—H. Classically, each "line" or "bond" in a formula such as this was simply a pictorial representation of unit combining power or valence, as no physical significance could be attached to it.

Difficulties arose in establishing certain structural formulas. For example, on assigning the most probable structure for acetylene, C_2H_2, not all of the valences of each of the carbon atoms appeared to be satisfied. It was therefore postulated that these "left-over" valences could mutually satisfy each other to give H—C≡C—H. Today we know that the structural formula which was assigned is the correct one, and that carbon is tetravalent in the compound. Nevertheless, in Kekulé's time there was no more "proof" for the structure just given (in regard to the arrangement of bonds) than for structure (I). If acetylene could definitely be considered as ethane



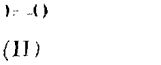
(I)

minus the four central hydrogen atoms, formula (I) could equally well "represent" the molecule, the unsaturated valences simply remaining "free." The other formula, involving the new concept of a multiple bond, was adopted because it preserved the tetravalence of carbon, although considering the large number of organic compounds in which carbon was unquestionably tetravalent, it was not altogether an unreasonable assumption. The classical concept of valence was extended by the adoption of this formula for acetylene. The valence of an atom in a compound could now be defined in terms of the number of attached bonds, rather than the number of attached atoms. Thus, nitrogen could be assumed to be trivalent in N_2 since N≡N could be proposed as a reasonable structure.

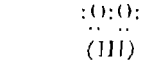
At the present time, when we speak of valence in electronic terms, the emphasis is almost entirely on the bonds linking the atoms rather than on the number of atoms, although, of course, the number of electrons involved will in part be dependent upon the number of atoms. Structural formulas are now written (either directly or by implication) so as to represent actual electronic structures. Since each of the classical bonds in acetylene is known to represent a shared pair of electrons, and since each carbon atom is sharing four pairs, we would state that each carbon is displaying a *covalence* of four. On the other hand, when the bond is *electrovalent*, or *ionic*, the term valence refers to the number of electrons that have been transferred from one atom to

another. Thus sodium in NaCl is said to have an ionic valence of 1, or +1 (since it is positively charged), while chlorine has an ionic valence of −1.

Even today, the exact electronic structures of some compounds have not been conclusively established, for example, the boron hydrides, which do not appear to follow the ordinary valence rules. Furthermore, there are some compounds of known structure that possess abnormal "arrangements" of electrons, that is, abnormal in regard to the number of electrons involved in bonding, their spatial distribution, or their spins. Thus it is not always possible to utilize the relatively simple concepts of the electronic theory of valence and to state the covalences or electrovalences of the atoms involved. For example, spectroscopic evidence appears definitely to exclude the classical bivalent formula for oxygen (II), which would also seem to be a reasonable structure in the Lewis theory (see p. 556), since by sharing two pairs of electrons both atoms could attain the stable octet configurations. Because of its paramagnetism the diradical structure (III) has been proposed (the single electrons remaining unpaired



(II)



(III)

and possessing parallel spins). Other structures involving three-electron bonds have also been considered for the oxygen molecule (ref. 15, p. 273), while the molecular orbital theory (see p. 568) describes its unusual properties in terms of one-electron π bonds (ref. 5, p. 18; ref. 3, p. 100).

Another unusual compound whose bonding stands in marked contrast to that present in the normal two-electron covalent bond is the hydrogen molecule-ion, H_2^+, characterized by the presence of a single one-electron bond. Although this molecule is only found spectroscopically (presumably because of its great tendency to attract another electron), it nevertheless possesses an appreciable bond energy. As will be discussed under "Quantum Theory of Valence," the "simplicity" of the molecule makes it of particular interest from the standpoint of quantum mechanics, as it enables very accurate calculations to be carried out.

While such compounds are of great interest theoretically, it should be emphasized that they are so exceptional in their structure and behavior that they do not thereby invalidate all of the normal valence rules established for the large majority of compounds. Similarly, it cannot be expected that these rules are obeyed under extreme conditions. For example, free radicals (possessing unsaturated valences) can be generated from a large number of compounds under certain conditions, such as high temperature. However, their intense reactivity and short lives should be proof enough of their abnormal electronic structure. See also *Radicals*.

Other compounds having unusual features from the point of view of valence include intermetallic compounds (see Vol. **1**, p. 559), the carbonyls (see Vol. **3**, p. 202), some carbides (*q.v.*), nitrides (*q.v.*), and borides, and certain coordination compounds (see Vol. **4**, p. 721).

Since we will be concerned with the fundamental nature of the chemical bond throughout this article, a formal definition should be given. Adopting the one given by Pauling, a chemical bond can be said to exist between two or more atoms when the forces acting between them are of sufficient strength to enable the group of atoms to act as an independent, and relatively stable aggregate (ref. 15, p. 3). Such a bond

may be ionic in character, as exemplified by sodium chloride, or covalent (nonionic) as in the hydrogen molecule. It may also possess properties that are "intermediate" in nature. Thus the carbon-fluorine bond, which is strongly polar, can be considered to be "in between" an ionic and covalent extreme, while the carbon–carbon bond in benzene has properties (such as bond length and chemical reactivity) that are in between those of a single and double bond. Other types of bonds will include the hydrogen bond and the metallic bond, as well as the rarer one- and three-electron bonds.

The interatomic, or valence, forces that result in the combination of atoms, forming stable (or relatively stable) compounds, should be carefully distinguished from the forces that cause the molecules themselves to be attracted to one another. These intermolecular forces will also include the attraction between the monatomic "molecules" of the rare gases, for example, since such atoms do not even combine with themselves. Such forces are responsible for the fact that all known gases can be liquefied, and they are represented by the constant a in van der Waals' equation (see *Gases and vapors*). At the present time they are frequently referred to as dispersion forces, first satisfactorily accounted for mathematically by London. Although they are much weaker than valence forces, they are exerted by all molecules, and they result either from molecules possessing permanent dipoles or, for example, in the hydrogen molecule, from possessing "momentary" or "instantaneous" dipoles. The existence of the latter in the hydrogen molecule is due to the fact that the electrons are in constant motion about the two positive nuclei, so that at any particular instant the centers of positive and negative electricity in the molecule do not coincide. The momentary dipole of an individual molecule induces momentary dipoles of opposite sign in neighboring molecules, and this results in an overall attraction between them.

The distinction between valence forces and intermolecular forces is not always completely clear cut, and it is sometimes difficult to prove definitely that a chemical bond exists between certain atoms or groups. In addition, in certain cases where bonding appears probable, it is not always possible to state exactly what kind of bond is involved. Examples of such borderline cases would include certain ions that are strongly hydrated in solution; the water (alcohol, etc.) of crystallization of certain substances; addition compounds such as naphthalene picrate; and aromatic π-bond complexes (for further discussion see ref. 7, pp. 4–69 and ref. 29, pp. 7–71).

Classical Valence Theory

The Dualistic Theory. Davy, in 1807, as a result of researches on chemical decomposition by electricity, postulated that chemical combination might be the result of the attraction of oppositely charged particles. Berzelius developed this concept into a full-fledged theory, which he first proposed in 1812. Berzelius assigned to every atom a positive and negative pole, although an atom such as chlorine was assumed to possess an excess of negative electricity, while others like the alkali metals were assumed to have an excess of positive electricity. In order to account for the more complicated compounds that could be formed from the combination of simpler substances, he assumed that chemical combination was a partial mutual neutralization. The dualistic theory was overthrown as a universal theory of combination largely because of its inability to account for the nature of organic compounds. Dumas, in his theory of substitution (1839), showed that chlorine could replace atom after atom of hydrogen in a given organic compound without markedly affecting its properties.

This was entirely contradictory to the concepts of the dualistic theory, for it meant that an electronegative element (chlorine) could, in effect, take the place of an electropositive element (hydrogen).

Valence as a Number. Frankland in 1852 put forward the idea that the atoms of each element had a definite and unique combining power, which determined the number of atoms of another element which could combine with it, and which he called its "atomicity." The term quantivalence was introduced by Hofmann in 1865, and this was later shortened to valence (from the German, Valenz) by Wichelhaus in 1868. Frankland originally thought that the valence of an element was always constant, but later that each type of atom had a fixed maximum combining power although all of it was not always used.

The Structural Concept. Kekulé and Couper independently in 1858 postulated the tetravalence of carbon and the mutual linking of carbon atoms. At about the same time, Butlerov emphasized the importance of a single formula to represent a compound (since up to this time different formulas for the same compound were used to express different reactions), while Cannizzaro corrected many erroneous atomic weights (for example, O = 8) and thereby played a vital role in the development of correct molecular and structural formulas. Kekulé proposed his "static" formula for benzene in 1866 and six years later his "dynamic" formula.

The Tetrahedral Concept. Shortly after Mendeleev had clearly established the periodicity of valence and many other properties of the elements, Van't Hoff and Le Bel in 1874 considered the stereochemical or spatial aspects of organic molecules, and Van't Hoff, in particular, emphasized the tetrahedral distribution of the valence bonds about the carbon atom. Baeyer, in his *strain theory*, postulated in 1885 that any deviation of the directed valences from the tetrahedral angle in a compound should result in a condition of strain. His conclusions concerning the lower cycloalkanes, namely that cyclopropane should exhibit the most strain and cyclopentane the least, are still valid today (with reinterpretation), but those concerning the higher cycloalkanes are not, since they are now known to exist in puckered and (relatively) strainless configurations (see Vol. **12,** p. 855).

Coordination Theory. Following the electrolytic dissociation theory of Arrhenius, which emphasized the marked differences in the properties of salts, or electrolytes, and the majority of organic compounds, Werner in 1892 proposed his coordination theory of complex compounds (see *Coordination compounds*, and *Stereochemistry (inorganic)*, Vol. **12,** p. 880). Werner postulated that the classical theory of valence was inadequate for the formulation of certain types of "molecular" compounds such as $CoCl_3.6NH_3$, and the type of structure he proposed was $[Co(NH_3)_6]^{3+}3Cl^-$. He assumed that certain atoms (for example, Co) were capable of combining with other groups or ions by means of "subsidiary" or "nonionizable" valences after their "primary" or "ionizable" valences were satisfied, the subsidiary valences being responsible for the formation of the complex ion. The number of groups attached to the central metallic atom (four or six being the most common) he called the coordination number. In regard to the structural relationships in such compounds, Werner's concepts are valid today, although his ideas concerning the nature of the valence forces involved in coordination were incorrect (see p. 562).

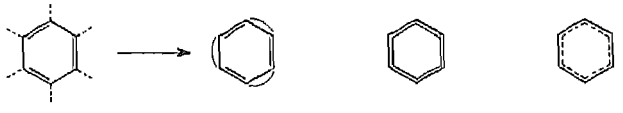
Theory of Partial Valence. To account for the properties of a carbon-to-carbon double bond, Thiele postulated in 1899 that the two bonds were not identical and that the second bond did not utilize as much "affinity" as the first, so that a certain

amount of affinity or "partial valence" would be left over. He explained 1,4-addition in butadiene by first assuming that since each of the four carbon atoms was connected to a double bond, each should possess a partial valence as shown by (IVa). However, since two carbon atoms joined by a single bond are normally capable (by suitable reactions) of being linked by a second bond, it appeared unlikely that the two free partial valences in the center of (IVa) would remain free but would mutually saturate

(IVa) (IVb)

each other (he termed this *conjugation*) to give (IVb). Bromine could then add to the 1,4-positions to give $CH_2Br—CH=CH—CH_2Br$, after redistribution of the valences.

To explain the saturated nature of benzene and the nonexistence of 1,2-disubstitution isomerism, Thiele assumed that the original "static" Kekulé formula was correct, which he portrayed as in (Va). The partial valences were then assumed to mutually saturate each other about the single bonds to give (Vb). Thiele believed that as a result of the complete neutralization of the partial valences, no distinction could be made between the three original double bonds and the three conjugated double bonds and that, in effect, benzene contained six "inactive" double bonds. His alternative formula for benzene was therefore written as in (Vc), later frequently drawn as in (Vd). There is an interesting resemblance (though purely formal) between



(Va) (Vb) (Vc) (Vd)

Thiele's theory and the molecular orbital concept of the double bond and its application to the benzene problem (see p. 580).

The Electronic Theory of Valence

It will be evident from the previous section that there was a need for a single theory that would unify the numerous facts and hypotheses of both inorganic and organic chemistry. This was not possible, of course, until the fundamental nature of matter was understood. The period from approximately 1895 to 1915 was an extraordinary one. A series of remarkable discoveries in physics, accompanied by even more remarkable theories, followed one another in rapid succession, many of which had a profound effect on theoretical chemistry. Only an outline of these developments can be given here (see also *Atoms and atomic structure*; *Isotopes*; *Nucleonics*; *Radioactive elements, natural*).

Atomic Theory (1895–1915). The modern era in atomic theory began just before the turn of the century with three important events: the discovery of x-rays by Röntgen in 1895 and, within the next two years, the discovery of radioactivity by Becquerel and of the electron by Thomson. Planck proposed his revolutionary quantum theory in 1900, postulating that the interchanges of energy between electromagnetic radiation and matter occurred in a discontinuous manner. In 1902, Rutherford and Soddy put forward the disintegration theory of radioactivity. Einstein published his paper on the special theory of relativity in 1905, and an important part of this theory was the concept that matter and energy were interchangeable. In the same year, he proposed the law of photoelectricity,

based on Lenard's experimental work, in which he postulated that electromagnetic radiation could exhibit both particle-like and wave-like characteristics. As will be described later (see p. 564), approximately twenty years later matter itself was discovered to have a dual nature. Certain radioactive elements had been found to possess identical physical and chemical properties and, when mixed, to be inseparable. Soddy in 1910 suggested that the nonradioactive elements might also represent mixtures of chemically inseparable substances, which he called isotopes, and three years later Thomson proved the existence of the isotopes of neon by positive-ray analysis.

In 1911 Rutherford postulated that the atom consisted of a minute, positively charged nucleus about which revolved a number of electrons sufficient to make it electrically neutral. Moseley, continuing the early work on secondary x-ray emission by Barkla, showed in 1913 that when the elements are arranged in a consecutively numbered series, the square root of the frequency of a definite spectral line increases linearly with the number of that element—the so-called *atomic number*. Because of the mathematical exactness of the law, it appeared that the atomic-number series was of greater significance than the atomic-weight series. It therefore seemed reasonable that Van den Broek's previous suggestion that successive elements differed by one unit in their positive nuclear charge and, therefore, by one external electron, was correct, although conclusive proof was not established until later. From a knowledge of the properties of isotopes and the radioactive elements, it was assumed that the nuclei of atoms above hydrogen contained electrons as well as protons. It was not until after the discovery of the neutron in 1932 that this was shown to be incorrect. However, since the chemical properties of an atom are almost entirely dependent upon the external electrons surrounding the nucleus (and usually only the outermost electrons), this discovery had little effect upon the electronic theory of valence.

Kossel and Lewis Valence Theory. While it had been realized by Thomson, Abegg, Drude, and others, that there was an intimate connection between the electrons and the valence of an element, the first satisfactory electronic theory was proposed by Kossel and Lewis, independently, in 1916. Both authors emphasized the fact that the electronic arrangements in the inert gases were the most stable structures, since they showed no tendency whatsoever for normal chemical combination, and that other atoms in their chemical reactions would try to attain the inert gas structures.

In both theories the electrons were regarded as surrounding the nucleus in concentric groups, and for the first three rare gases the stable groups were assumed to be 2 for helium, 2,8, for neon, and 2,8 8, for argon. Kossel considered the electrons to be in motion about the nucleus and that the groups of electrons were arranged in concentric rings in one plane, while Lewis assumed that the electrons took up fixed positions at the corners of concentric cubes (except for the two electrons in the first shell). Both models have, of course, long since been discarded, although Kossel's dynamic model was closer to the truth. Nevertheless, the basic idea of stable groupings, or shells, is considered valid today.

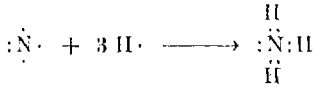
According to Kossel, the valence of an element was considered to be equal to the number of electrons it must lose if electropositive or gain if electronegative, in order to attain the same electronic structure as an inert gas. For example, the elements fluorine, neon, and sodium possess 9(2 + 7), 10(2 + 8), and 11(2 + 8 + 1) electrons, respectively. Sodium would therefore be expected to lose one electron readily so as to attain the stable neon structure, while fluorine would be expected to gain one electron. Designating only the electrons in the outermost shell, the reaction between the two elements can be written:

$$Na\cdot + \cdot\ddot{\underset{\cdot\cdot}{F}}: \longrightarrow \left[:\ddot{\underset{\cdot\cdot}{Na}}:\right]^{+}\left[:\ddot{\underset{\cdot\cdot}{F}}:\right]^{-}$$

While Kossel's theory accounted satisfactorily for the elements close to an inert gas in the periodic table, it could hardly account for others farther away. Nitrogen, according to Kossel, should tend to form an N^{3-} ion, which was certainly unlikely. Lewis,

on the other hand, had postulated that the type of combination resulting in a direct gain or loss of electrons, later called *electrovalence* by Langmuir, was solely restricted to ionic compounds or salts. In addition, he proposed that two atoms could, in effect, attain the inert gas structure by the process of sharing electrons. Thus Lewis considered that two fluorine atoms, for example, could attain the neon configuration by mutually sharing a pair of electrons as shown diagrammatically in the following equation:

Nitrogen, with five electrons in its outer shell, requires three more to complete its octet. Hydrogen, which has one electron, requires one more in order to possess the helium configuration. It therefore appeared reasonable that nitrogen could complete its octet, and each hydrogen its duet, by the mutual sharing of three electrons from the nitrogen and three electrons from three hydrogen atoms, as shown below:



This type of chemical combination, later called *covalence* by Langmuir, occurs very frequently in the organic compounds. Lewis proposed that the sharing of electrons could only occur in pairs, and as evidence for this he pointed out that with only a very few exceptions chemical compounds contained an even number of electrons. Examples of compounds containing an uneven number, which he called "odd" molecules, are nitric oxide (11 electrons), nitrogen dioxide (17 electrons), and chlorine dioxide (19 electrons). Such molecules show a tendency to attain an even number of electrons by dimerization; for example, NO_2 readily forms N_2O_4.

He considered a shared pair of electrons to be equivalent to the classical valence bond, and the number of shared pairs to give the valence of the atom. Thus nitrogen is considered to be trivalent in NH_3 in the electronic theory as well as in classical theory. Double bonds were considered to involve the sharing of two electron pairs and triple bonds the sharing of three pairs.

Lewis postulated that the electron pair in a molecule such as H_2 would be symmetrically placed between the two atoms, but that in HCl, for example, the pair would be displaced toward the more electronegative chlorine (or, as we would say today, the electrons in their motion about both nuclei would be expected to spend more time in the neighborhood of the chlorine atom, that is, the electron density is higher). Thus only the HCl molecule should possess a dipole moment. He assumed that this type of electron displacement (now called the *inductive effect*) could be relayed in a chain of atoms, and also that the longer the chain, the weaker would be the effect at the end of the chain. Chloroacetic acid is therefore more acidic than acetic acid because the chlorine atom ultimately causes the oxygen attached to the ionizable hydrogen to be more positive in the former compound, and therefore better able to repel the proton.

The concept of electron displacements was of the greatest importance, for by showing that they could cause a molecule to vary all the way from a nonpolar-covalent extreme to a completely ionic extreme, the close relationship between the ionic and covalent compounds (and therefore inorganic and organic chemistry) was finally established. Moreover, such concepts were responsible for bringing about a very rapid

development in the electronic interpretation of reaction mechanisms, particularly by Lapworth, Lowry, Robinson, and Ingold.

The transition from an ionic compound to a covalent one was interpreted by Fajans in 1923 in terms of the deformation of the electron orbits of ions. He showed that such deformations are dependent upon the sizes of the ions and upon their charge, and that the deformation of a cation is usually very small in comparison with that of an anion. The greater the attraction between any two ions, the greater is the resulting deformation, and a point will be reached where the latter is so great that the electrons will cease to belong to one atom or the other but will be shared between them, that is, the electrovalency has passed over into a covalency. Although the transition between the two bond types is not very sharp, the extremes of electrovalence and covalence are easily recognized. In general, the two classes of compounds differ markedly in physical and chemical properties. Ionic substances are easily soluble in polar solvents such as water, and give solutions that readily conduct electricity. Covalent substances, on the other hand, usually exhibit greater solubility in the nonpolar solvents, giving solutions that are not good conductors of electricity. Ionic substances have very high melting and boiling points, while those of the covalent compounds are normally much lower. Ionic reactions are rapid, while those involving covalent substances are usually rather sluggish.

The molecules of covalent substances preserve their "identity" to a large extent when in the liquid, or even solid, state because the attraction between such molecules (the van der Waals attraction) is not usually great enough to cause actual bonding. However, this is not the case with the ionic substances. Up to now, the ionic bond has been pictured as one that exists in an isolated "molecule," or ion-pair, such as Na^+Cl^-, although the attraction between one ion-pair and another is strong enough to result in bonding. Let us consider the magnitude of the forces involved (see ref. 29, p. 8).

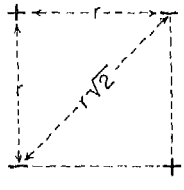
The electrostatic attraction between an isolated NaCl ion-pair is given approximately by the expression, $-e^2/r$, where e is the magnitude of the electric charge and r the interionic distance. This represents the amount of energy (approximately 100 kg.-cal./mole) that would be required in order to separate the two ions completely. It should be pointed out that, while the forces involved in both ionic and covalent bonds theoretically fall off to zero only at infinite separation, the decrease is very much more rapid for covalent forces. The total attractive force between two isolated ion-pairs would be $-2e^2/r$, but if the ion-pairs are allowed to approach one another so that the four ions are arranged at the four corners of a square, as shown in Figure 1, the total attractive force is $-e^2/r \times [4 - (2/\sqrt{2})]$ or $-2.586e^2/r$. Since the difference, namely $0.586e^2/r$, represents the energy that would have to be supplied to dissociate $(NaCl)_2$ into 2NaCl, it is obvious that the "dimer" is considerably more stable than two isolated ion-pairs. Similarly, a "tetramer," $(NaCl)_4$, consisting of eight ions arranged at the corners of a cube, as shown in Figure 2, is more stable than two isolated dimers.

Calculation shows that for a crystal of NaCl, consisting of N molecules (where N is very large), the total energy changes (approximately) from $-Ne^2/r$ for N isolated molecules to $-1.747Ne^2/r$ for the whole crystal (for other substances the energy will, in part, be determined by the specific geometry of the crystal). It is therefore easy to understand why sodium chloride, and the ionic compounds in general, have high melting points and boiling points.

Lewis' Electronic Generalizations. The concept of oxidation and reduction was generalized by Lewis. A substance is said to be oxidized (and this applies to atoms, ions, or molecules) if in a chemical reaction it loses electrons, and to be reduced if it gains electrons (see *Oxidation-reduction*). In addition, Lewis generalized the concept of acidity and basicity. He defined a base as any substance capable of furnishing an unshared pair of electrons for the formation of a chemical bond (see p. 561) and an acid as any substance which is able to accept such a pair for bond formation (see *Acid-base systems*).

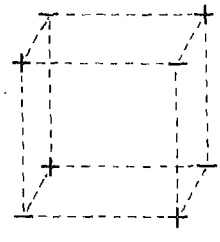
Electron Configurations. A knowledge of the electronic configurations of all the elements in the periodic table was of fundamental importance to the further development of the electronic theory of valence. While it is not possible in this article to discuss the configurations in detail, it is important to understand the general principles.

Largely on the basis of the Rutherford model of the atom and Moseley's law, it was assumed that the total numbers of electrons in the rare gases were helium (2 electrons), neon (10 electrons), argon (18 electrons), krypton (36 electrons), xenon (54 electrons), and radon (86 electrons). It therefore seemed reasonable to suppose that the differences in these numbers (after helium), namely, 2,8,8,18,18,32, represented the



Dimer

Figure 1.



Tetramer

Figure 2.

exact electronic configurations, shell by shell, of each of the rare gases. For example, following argon (2,8,8), it was expected that for successive elements up to krypton all of the additional electrons would enter the fourth shell, and that the configuration of krypton would therefore be 2,8,8,18. In fact, Langmuir made this assumption while developing the Lewis theory.

However, a detailed study of the properties of the elements in the periodic table shows that this could hardly be the case for the longer periods. Bury, on chemical grounds, and Bohr, on physical grounds, in 1921 showed that the correct electronic structures were undoubtedly those shown in Table I.

The important points to note are: (*1*) The maximum number of electrons that a group or shell can contain is $2n^2$, where n is the principal quantum number (see p. 565). (*2*) The outermost shell of each of the rare gases contains a group of only 8 electrons. (*3*) The groups attain a state of comparative stability when they have 8 or 18 electrons, even if they are capable of expanding their shells in the later periods. The experimental evidence for Table I (apart from the knowledge of the chemical properties of the elements) and, in particular, for the elaborate chart given in Vol. **2**, p. 210, is obtained from many sources, including optical spectra, x-ray emission and absorption spectra, and the ionization potentials of the elements.

The chart of configurations proposed by Bohr (1) (given in part in Table I) was

TABLE 1. Electron Configurations of the Inert Gases.

Shell	K	L	M	N	O	P
n	1	2	3	4	5	6
He	2					
Ne	2	8				
A	2	8	8			
Kr	2	8	18	8		
Xe	2	8	18	18	8	
Rn	2	8	18	32	18	8

based on the idea that the electrons possessed definite circular and elliptical orbits, and he characterized the orbits in terms of only two quantum numbers (which represented the different energy states of the electrons). Bohr also assumed that the electrons in a completed group were equally distributed into various subgroups. We now know that each electron has to be characterized by four quantum numbers which, according to quantum mechanics, cannot be described in terms of simple orbits. In addition, the maximum number of electrons in the various subgroups are known to be 2,6,10,14 (see *Atoms*). In the next few years Bohr's concepts underwent a rapid development (for an interesting discussion of this period, which ended with the adoption of quantum mechanical concepts, see ref. 24, pp. 25–50). Nevertheless, it was possible for both Bohr and Bury, with the knowledge at their disposal, to relate in a general way the properties of many of the elements with what might now be called their "over-all" configuration (that is, one which merely tells us the total numbers of electrons in each shell). Let us consider the type of reasoning employed at that time with a few examples.

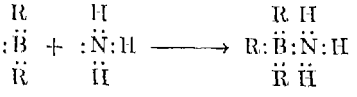
Helium possesses two electrons which are assumed to be in the first (or K) shell. Since helium is inert chemically, its shell was assumed to be complete, and therefore the introduction of a third electron in lithium is presumed to occur in a new (L) shell. Spectroscopic evidence definitely points to this. In addition, while the ionization potential for the removal of one electron in helium is approximately 24.5 volts, it requires only about 5.4 volts to remove the first electron in lithium. It is evident that this single, easily removable electron is responsible for giving lithium its univalent and electropositive character. Similarly, the identical change in properties which we find when we go from any other inert gas to its succeeding alkali metal, shows that a corresponding change in structure occurs in every case (again corroborated spectroscopically and by ionization potentials). Since each of the halogens come just *before* an inert gas and since each possesses a total of 7 electrons in its outer shell, the halogens would be expected to be predominately univalent and electronegative in character.

The properties of the corresponding elements in the two short periods follow in a fairly regular manner from the identical electronic configurations of the outer shells. The properties of the transition elements in the first long period (scandium to nickel) can be understood if after calcium (configuration 2,8,8,2) the third (K) shell starts to build up until a maximum of 18 electrons is reached. The electronic structures of the rare earth metals are particularly interesting. The configuration of barium, which is just before lanthanum, is 2,8,18,18,8,2. However, the fourth (N) shell is capable of

holding a total of 32 electrons, and it is in the rare earth series that this shell is progressively built up (although not in a perfectly regular manner). Since the electrons are added to a shell that is relatively deep within the atom, the rare earths are remarkably similar to one another in physical and chemical properties.

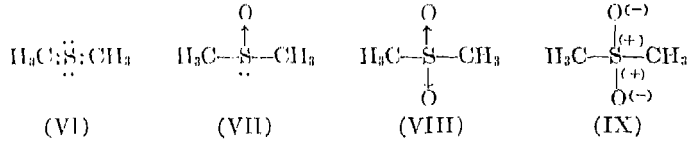
The Coordinate Bond. In 1927 there appeared a comprehensive book on valence by Sidgwick (24). In contrast to many of the chemists of that time, Sidgwick rigidly conformed to the demands of the physicist, and as a result many of his conclusions are still valid today, subject, of course, to a reinterpretation in the light of quantum mechanical concepts.

Lewis had pointed out that under certain conditions those atoms that possessed an unshared pair of electrons should be capable of sharing both electrons with other atoms or groups. For example, since in boron trimethyl it can be seen that boron is only sharing six electrons, the combination between that compound and ammonia would appear to involve the sharing of both of the electrons on the nitrogen atom, as shown in the following equation:



He also postulated that the formation of complex salts might involve a similar type of sharing. Sidgwick developed the concept more fully and termed this type of valence *coordinate valence*.

Similarly, the sulfur atom in methyl sulfide (VI), is seen to possess two unshared pairs of electrons, each of which is capable of sharing its electrons with one or two oxygen atoms to form a sulfoxide or sulfone, respectively. To show that the electrons involved in the sharing came from the sulfur, Sidgwick wrote these structures as shown in (VII) and (VIII). The *coordinate bond* has also been called a *dative bond*, a *semipolar double bond*, or simply a *semipolar bond*. Since this type of sharing causes the



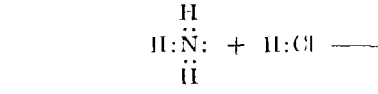
(VI) (VII) (VIII) (IX)

donor atom to have a formal unit positive charge and the acceptor to have a formal unit negative charge, methyl sulfone is also represented by the alternative formula (IX). The word formal is used because a structure like (IX) does not accurately represent the distribution of the charges. Part of the unit charges will be relayed inductively to the other atoms and groups, for example, the positively charged sulfur in (IX) strongly attracts the electron pair in the sulfur-methyl bond, and this causes the methyl group to have a partial positive charge.

It should be pointed out that while the nitrogen-oxygen bond in the amine oxides, R_3NO, is considered today to be definitely semipolar, the situation in regard to the sulfoxides and sulfones is not entirely clear. Sulfur, in contrast to nitrogen, is capable of expanding its valency shell, so a covalent double-bonded structure, S=O, should be possible. At the present time the sulfur-oxygen bond in such compounds is considered to be best represented as a *resonance hybrid* (see p. 577) whose actual electronic structure is somewhere between the semipolar and double bond structures. Nevertheless, the fact that sulfoxides of the general type RR′SO are capable of exhibiting

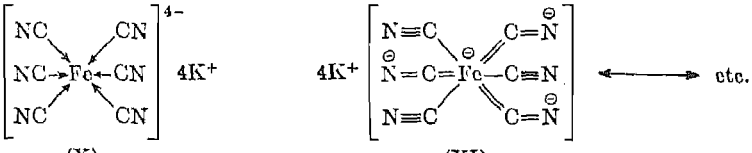
optical isomerism would indicate that the sulfur-oxygen linkage in such a compound cannot be a full-fledged double bond, as this would give the molecule a plane of symmetry and isomerism would not be possible (see Vol. **12,** p. 860; Vol. **13,** p. 353).

Onium Compounds. The electronic theory gives a satisfactory explanation of the nature of the linkages in compounds such as ammonium chloride and the quaternary ammonium compounds. Thus the reaction between ammonia and hydrogen chloride can be interpreted as shown in the following equation:



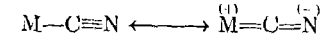
Once the hydrogen ion becomes coordinated with the unshared pair on the nitrogen atom, of course, all distinction between it and the three other hydrogen atoms disappears, and the four covalent bonds attached to the nitrogen become identical. Because of the positive charge, however, the nitrogen is said to exhibit an ionic valence of $+1$, in addition to a covalence of 4 (see *Onium compounds; Quaternary ammonium compounds*). As might be expected from the discussion of formal charges, the whole of the positive charge in the ammonium ion is not exclusively located on the nitrogen atom, but can be considered to be transferred in part to each of the hydrogen atoms.

Complex Compounds. Groups such as H_2O, NH_3, Cl^-, and CN^-, which are capable of forming complex salts with metallic ions, all possess unshared pairs of electrons. It therefore was assumed that the coordinating groups were actually attached to the central atom by means of semipolar bonds (see *Coordination compounds*). However, this is by no means always the case. For example, potassium ferrocyanide is usually represented by the structural formula (X). While this is a very "con-



(X) (XI)

venient" formula, which emphasizes the fact that during formation of the complex ion the unshared pairs of electrons on the cyano groups are involved, it is actually a very unlikely structure. Since it involves the uncharged —C≡N group, structure (X) would give the central iron atom a charge of $4-$, although iron normally tends to assume a positive charge. However, the cyano group is an electronegative group and because it possesses a multiple bond, resonance of the type shown below should be possible:



Pauling and others have therefore suggested that potassium ferrocyanide is much better represented as a resonance hybrid that will include structures such as (XI). In structure (XI), which represents only one of many possibilities, it will be seen that the iron possesses only a single negative charge, which is much more probable than the $4-$ in structure (X). In the actual hybrid structure, of course, the electron distribution is such that all of the bonds become equivalent to one another (for a very

detailed discussion of the electronic structures of complex compounds, see ref. 27, pp. 343–94).

Valence Shell Expansion. While many elements combine so as to attain the configurations of the inert gases, there are quite a number of exceptions to the octet rule, for example, PF_5 (10 electrons), SF_6 (12 electrons), and OsF_8 (16 electrons). The central atom in the coordination compounds is also frequently surrounded by more than eight electrons. Sidgwick tabulated the maximum covalences that appeared to be possible for the elements, and found that all atoms capable of valence shell expansion were outside of the first short period. Elements in the latter period are not capable of exhibiting a covalence greater than four. Elements in the second short period and first long period can display a maximum covalence of six. The heavier elements are capable of having a maximum covalence of eight.

Sugden, in an attempt to preserve the octet rule, postulated that in PF_5, for example, three of the fluorine atoms are attached to the phosphorus atom by ordinary "duplet," or electron-pair, linkages and that the other two are joined by means of "singlet" linkages, involving only one electron for each bond. Singlet linkages are now regarded as being very rare, and the modern explanation for the existence of such compounds is based on the concept that for the atoms of the higher elements, "vacant" orbitals (of relatively low energy) can be called upon for "additional" bond formation. The quantum theory of valence also gives a satisfactory explanation of the strengths of such bonds as well as their directional characteristics (see below and refs. 16,19).

Valence shell expansion is not a complete explanation of the phenomenon of variable valence. Other factors must be taken into account, such as the utilization of unshared pairs of electrons (as previously described) and the tendency for atoms to form electrovalent bonds in addition to covalent bonds.

See also *Phosphorus compounds, inorganic,* Vol. **10,** p. 462; *Sulfur compounds—structure,* Vol. **13,** p. 374.

Quantum Theory of Valence

While the electronic theory of valence was very successful in correlating many facts concerning chemical combination, it was still largely descriptive in nature. Without the necessary tools for computation, it was unable to explain satisfactorily why a covalent bond should exist at all. Ultimately, the incompleteness of the electronic theory was due to the failure of classical physics to yield the right answers for particles and events of atomic dimensions. When applied to the Rutherford model of the atom, classical physics predicted that it could not possibly be stable. If the planetary electrons were at rest, then, according to the laws of electrostatics, they should move into the nucleus under the action of the Coulombic attraction. On the other hand, if the electrons were in motion, classical theory predicted that the acceleration experienced by the electrons in their necessarily nonlinear orbits around the nucleus would lead to loss of kinetic energy by emission of radiation, and the electron would spiral into the nucleus. It was suggested by Bohr in 1911 that Rutherford's picture of an atom was essentially correct, but that the application of classical mechanics to an atomic system was not correct. Bohr (1) postulated that certain energy states were available to electrons in atoms, and that in these states, which he called stationary, the electrons could undergo circular (accelerated) motion about the nucleus without

radiating energy. Similar postulates concerning the restriction of atomic or electrical oscillators to certain energy states (quantization of energy) had been made previously by Planck (1900) in treating the spectral distribution of energy from a black-body radiator and by Einstein in his study of the photoelectric effect.

Bohr assumed that the angular momentum of the electron about the nucleus was quantized:

$$2\pi p_\phi = nh \tag{1}$$

where p_ϕ is the orbital angular momentum, h is Planck's constant (which first appeared in Planck's work mentioned above), and n is an integer, 1,2,3,. . . . This assumption departs from classical mechanics, which would permit any value of p_ϕ. If we take as our model a positive nucleus of charge 1 and one electron, that is, the hydrogen atom, then:

$$\frac{e^2}{a^2} = \frac{mv^2}{a} \tag{2}$$

where e is the electronic charge, a is the distance of the electron from the nucleus, v is its velocity, and m its mass. According to equation (2), the centrifugal force that tends to cause the electron to leave the nucleus is counterbalanced by the electrostatic attraction. The restrictions expressed in equations (1) and (2), when applied to the classical problem of the dynamics of a body moving in a circular orbit, lead to the following expression for the total energy of the electron, W:

$$W = -\frac{2\pi^2 me^4}{n^2h^2} \tag{3}$$

The electron can therefore have only certain energies, W_n, which are proportional to n^{-2}, where n is an integer. The energy of the electron is said to be quantized, and n is called a *quantum number*.

The determination of the possible energies of the electron in the hydrogen atom enabled Bohr to calculate with remarkable accuracy the frequencies of the principal lines in the spectrum of atomic hydrogen, and of hydrogen-like species such as singly ionized helium. This was done through the postulate $\Delta E = h\nu$ where ΔE is the energy difference between two electronic levels, h is Planck's constant, and ν is the frequency of the absorbed or emitted light. The Bohr theory was generalized by Wilson and Sommerfeld (1915) with the introduction of elliptical orbits. The theory became extremely important in the interpretation of spectra, and formed the qualitative basis for the theories of valence put forward by Lewis and Langmuir around 1916. On the other hand, the theory failed in its quantitative application to nonhydrogen-like elements, and could not be extended to molecules. Nevertheless, the initial successes of the theory, and the qualitative insight which it provided into the electronic theory of chemistry, emphasized the need for a radical departure from classical mechanics in treating atomic and molecular systems, and paved the way for a more general form of quantum mechanics.

Quantum mechanics, as we know it today, had its inception in theoretical speculations put forward by de Broglie in his doctorate thesis in 1923. Einstein (1905) had postulated his photon or particle theory of light, in order to account for photoelectric phenomena. On the other hand, the traditional wave theory of light was well-established from such phenomena as interference, diffraction, and refraction. De Broglie accepted this dual nature of light as being inherent, and suggested that such a dualism was also characteristic of atomic particles. He associated with every particle a wave, whose wave length was inversely proportional to the mass of the particle. Since even atomic particles are extremely heavy as compared with photons, the wave lengths associated with them would be very short indeed, and hence might escape detection. Theoretically, however, matter should, under the right circumstances, show the interference effects characteristic of waves. These suppositions were supported experimentally in the later work of Davisson and Germer (1927), who found that electrons scattered by crystals show wave-like interference.

Stimulated by de Broglie's work, Schrödinger (1925) applied to atomic systems certain dynamical equations which were appropriate to wave systems. At the same time, Heisenberg and Born and Jordan constructed a new mechanics using matrix algebra. Schrödinger was able to show that both treatments were mathematically equivalent. The Schrödinger mechanics, or *wave mechanics*, requires less abstruse mathematics than Heisenberg's methods, and will be the basis of the following discussion.

According to wave mechanics (6,16,27), for any given atomic system, there exists a function of the coordinates of the system, ψ, such that the value of $\psi^2 d\tau$ at a given point is proportional to the probability of encountering an electron of the system in a small volume element $d\tau$ surrounding the point. All of the information which we can know about an atomic system is embodied in ψ. The probability interpretation of ψ was first suggested by Born and Jordan (1927), and this viewpoint is helpful in attaining a physical picture or model, based on the results of wave mechanics.

A second postulate, which further defines ψ, requires that it be a solution of the differential equation:

$$-\frac{h^2}{8\pi^2 m}\nabla^2\psi + V\psi = E\psi \tag{4}$$

where ∇^2 is the Laplacian operator (equal to $\partial^2/\partial x^2$ in one-dimensional space, and $\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ in Cartesian coordinate three-dimensional space), E is the energy of the electron, m is its mass, and h is Planck's constant. V is the potential energy of the electron, and is a function only of the coordinates of the system. Equation (4) is often called the Schrödinger equation, or, the wave equation because of its resemblance to equations governing wave motion. For this reason, the function ψ is called a *wave function*. It may be noted that as a postulate, the wave equation is not immediately related to any obvious experience, as are Newton's laws of motion. Intuition based on mathematical analogies led Schrödinger to his equation, but the equation itself has no physical meaning, and its use as a postulate is justified because, as a calculating device, it yields answers which agree with experiment. This denial of interpretation might have been extended to the wave function ψ, but the concept of ψ^2 as a probability distribution function is extremely valuable. Such an interpretation can give us a physical picture that is often helpful to the understanding. Moreover, the interpretation of ψ may allow a qualitative extrapolation of quantum mechanical results for simple systems to more complex systems not amenable to calculations.

Generally, the detailed solution of the Schrödinger equation is tedious, even for such a simple case as the hydrogen atom (for which $V = -e^2/r$, where r is the distance of the electron from the nucleus), and may become impossible in closed form for only slightly more complicated cases; for example, the helium atom. However, certain features of the solutions, ψ, can be indicated. These solutions are required always to be well-behaved: continuous, bounded, single-valued, etc. This serves to eliminate physically meaningless functions that might also be solutions of equation (4). In addition, the criterion of good behavior requires that $\lim_{r\to\infty} \psi(r) = 0$, corresponding to zero probability that the electron in the unperturbed atom will have left completely the neighborhood of the positive nucleus.

The nature of the potential function V is also of great importance in determining the nature of the solutions of the Schrödinger equation and the allowed values of the energy parameter E. For $V = 0$, that is, a particle in field-free space, it is found that a well-behaved ψ exists consistent with *any* value of the energy $E>0$. On the other hand, when $V = -e^2/r$, or V has some other form which restricts electrons to some particular region of space, then the Schrödinger equation has well-behaved solutions, ψ, for only certain values, E_n, of the energy, E. Quantization of the energies of electrons is therefore a natural result of requiring those electrons to be restricted by the potential function to certain regions of space. As a result of this limitation on the freedom of electrons by the positive potential fields associated with atomic nuclei, the energies of electrons in atoms and molecules will be quantized.

The values of E that yield acceptable solutions of equation (4) are related to the integers, $n = 1,2,3, \ldots$. An energy level is therefore specified by the quantum number n, which is called the *principal quantum number*. As a rule, the electron will have a higher energy the greater its distance from the nucleus. The values of E_n increase with n, so that higher values of n will be correlated with larger values of the average distance r, of the electron from the nucleus. The expression "average distance" is employed here, since, according to the probability interpretation of ψ^2, the electron cannot be said to travel in a discrete orbit. The value of E_n does not, however, fluctuate about an average value, as does the distance r. This is possible, of course, because E_n is the total energy of the electron, so that a variation in potential energy brought about by a change in r is offset by a change in kinetic energy.

The position of an electron relative to the nucleus is specified by two coordinates other than the distance r. The three (spherical) coordinates required are shown in Figure 3. Two other quan-

tum numbers are correlated with the presence of the angular coordinates θ and ϕ, in the same sense that the quantum number n is correlated with the coordinate r. These are l, the *azimuthal quantum number*, and m, the *magnetic quantum number*. A fourth quantum number which is not implicit in the Schrödinger equation, but is required by physical theory, is s, the *spin quantum number*. The specification of these four quantum numbers is sufficient to describe the energy, angular distribution, and magnetic moment of an electron. Corresponding to a given set of these quantum numbers is a wave function, ψ, which is often called an *atomic orbital*.

The shapes of the atomic orbitals are determined by the quantum number l. An electron for which $l = 0$ is called an s electron. The time-average distribution of an s electron about the nucleus is spherical (see Fig. 4a); that is, the probability of encountering the electron at a given distance from the nucleus is constant, and independent of the direction from the nucleus. When $l = 1$, however, there are three possible atomic orbitals, called p_x, p_y, and p_z orbitals, in which the probability of encountering the electron at a given distance from the nucleus is not independent of the direction

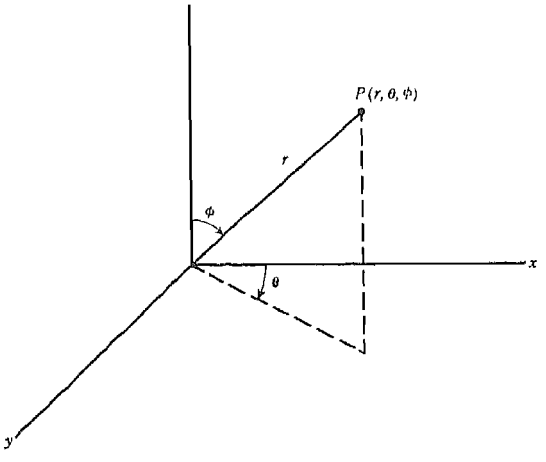


Fig. 3. Spherical coordinates r, θ, and ϕ of the point P.

from the nucleus. These orbitals are shown in Figures 4b, c, and d. For the p_x, p_y, and p_z orbitals, the probability of encountering the electron at a given distance from the nucleus is maximal along the x-, y-, and z-axis, respectively. As will be shown later, the shapes of these orbitals are important in formation of chemical bonds. Higher values of l are characterized as $d(l = 2)$, $f(l = 3)$, $g(l = 4)$ orbitals, etc. The values which l can assume are restricted to the integers from one through $(n - 1)$. For a value of $n = 1$, therefore, the allowed value of l is zero, and electrons with this value of n can be only s electrons. When $n = 2$, l can assume the values 0 or 1, and both s electrons and p electrons are possible.

The magnetic quantum number m determines physically the splitting of energy states (and hence of spectral lines) when an atom is in a magnetic field (the Zeeman effect). m can assume values of $-l, \ldots, -2, -1, 0, 1, 2, \ldots, l$. For $l = 0$, m can be only 0. For $l = 1$ (p electron), m can have the values -1, 0, $+1$. These three values of m account for the existence of the three kinds of p orbitals, p_x, p_y, and p_z. In the absence of a magnetic field, these three values of m, and hence the three p states, have exactly the same energy for a given n. Wave functions of this kind that have different mathematical forms (the three p states differ by rotation of the coordinate axes) but correspond to exactly the same energy are said to be *degenerate*. The d states ($l = 2$) show a fivefold degeneracy, corresponding to the five possible values of m. In the presence of a magnetic field, the three rectangular coordinates are no longer equivalent, and degeneracy is removed to a certain extent, for both p and d states.

The spin quantum number s (not to be confused with the s electron, for which $l = 0$), can take only two values, $\pm\frac{1}{2}$, corresponding to a clockwise or counterclockwise direction for the electron spin. The value of s has a minor effect on the energy of the electron, but its effects are observable in the fine structure of the spectrum of the hydrogen atom, and the multiplicity (singlets, doublets, etc.)

of lines in the spectra of more complicated atoms. Spin is also of importance in the theory of atomic structure, and appears in conjunction with the Pauli exclusion principle. According to the latter, no two electrons assigned to a given atom can have exactly the same set of quantum numbers. In the helium atom, for example, in which two electrons are assigned quantum numbers $n = 1$, $l = 0$, $m = 0$, the two electrons must differ in the fourth quantum number s. This particular state of the helium atom is possible, therefore, only if the spins of the electrons are opposed. Electrons of this kind, which are in the same space orbit with opposed spins, are said to be *paired*.

The interpretation of the quantum numbers given above is not unique. Thus, l has been correlated with the *angular orbital momentum* of the electron, whose value is $\sqrt{l(l+1)}h/2\pi$, and s is correlated with the *spin angular momentum* having a value of $\sqrt{s(s+1)}h/2\pi$. The values of l and s therefore determine the magnitudes of two vectors. The quantum number m determines the value, $mh/2\pi$, of the projection on the z-axis of the vector corresponding to l, and therefore the direction in space of that vector. These considerations are derived from the vector model of the atom, and relate the quantum numbers to dynamical quantities of classical physics. However, the significance ascribed in the text to these quantum numbers is of greater utility than the vector concepts in application to molecules. The vector model finds its greatest use in the interpretation of atomic spectra.

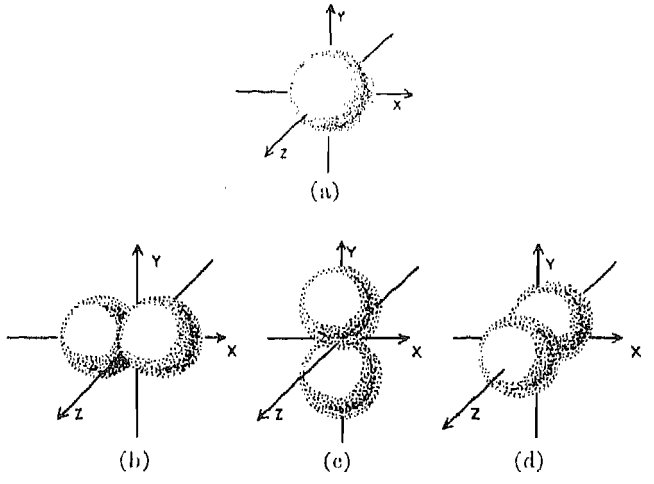


Fig. 4. (a) *s* atomic orbital; (b), (c), and (d) are p_x, p_y, and p_z orbitals, respectively (13a).

With the Pauli exclusion principle, and a knowledge of the relative energies of the various orbitals, it is possible to delineate the electronic states of the elements of the periodic table (27). The different states are given by the symbols *ns*, *np*, *nd*, etc., where n is the principal quantum number. In the hydrogen atom, the electron is in a $1s$ state. In helium there are two electrons in $1s$ states; this is indicated by $1s^2$, where the superscript indicates the number of electrons in the particular level.

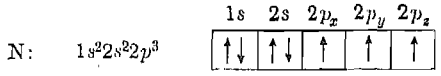
From a study of the spectra of the elements, the sequence of energies for the various electronic levels has been found to be:

$$1s<2s<2p<3s<3p<4s\sim 3d<4p<4d\sim 5s<5p<5d\sim 4f$$

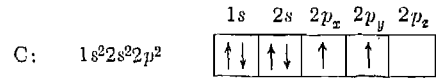
Generally the energies increase with n, as mentioned before. For a given n, the states with higher values of l have higher energies. However, the $3d$ level has about the same energy as the $4s$ level, and the $4f$ level is definitely out of sequence, lying higher than the first two sublevels in the shell $n = 5$.

To construct the most stable electronic configuration of an atom of atomic number Z, a positive nucleus of charge Z is considered, and Z electrons are fed into the lowest energy levels in accord with the above sequence and Pauli's exclusion principle. Another principle, Hund's rule, is also invoked

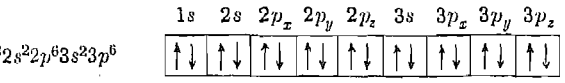
in this assignment: electrons tend to avoid being in the same space orbit. Space does not permit the derivation of the electronic configurations of all the elements in the periodic table, but we can illustrate the procedure with two elements. Nitrogen has seven electrons in its outer shell ($Z = 7$). Two of these can be placed into the lowest, 1s orbital with opposed spins. Two more can be paired in the 2s orbital. In accord with Hund's rule, the remaining three electrons are assigned one each to the p_x, p_y, and p_z orbitals. The electronic structure of nitrogen is represented as follows, where the arrows indicate spin direction:



This procedure leads to the following configuration for carbon:



The configuration for the inert gas argon is:



The configuration ns^2np^6 occurs in all of the noble gas outer shells, and is a particularly stable arrangement. This observation is important as a determinant of the number of bonds that an element can form; for example, by accepting three electrons, nitrogen can attain this noble gas configuration. Hence nitrogen should show a valence of three. In the case of carbon, whose electronic structure given above indicates a valence of two, other considerations become important, and will be discussed subsequently.

The inversions in the expected sequence of energy levels mentioned above are due principally to screening of electrons in outer valence shells from the nucleus by completed inner shells. This complicates the sequence in which the levels become filled with increasing atomic number. Thus, after argon, which has a stable $3s^2 3p^6$ shell, electrons go into the 4s shell rather than the 3d (which has about the same energy as the 4s shell). After this, the 3d shell begins to fill in the series of transition elements from scandium (atomic number 21) through copper (atomic number 29), while the 4-level continues to possess one or two s electrons. A similar situation exists with regard to the 4f shell, which lies above the 5s and 5p shells in energy, and has about the same energy as the 5d shell. In the "building-up" process, electrons go into the 5s and 5p levels first, and one goes into the 5d level, after which the 4f shell begins to build up. This gives the rare earth or lanthanide series. Since the outer valence shells of these elements are alike, they are chemically alike, which causes them to occur together in nature, and makes their separation very difficult.

The concept of orbitals about a positive nucleus has been extended to molecules (3). *Molecular orbitals* are wave functions that describe the electron distribution about several positive nuclei, rather than a single central nucleus, as in atoms. The assignment of electrons to molecular orbitals is accomplished in the same way as for atoms, in such a manner that the Pauli principle is not violated. The exact calculation of electron distributions and energies by means of the Schrödinger equation becomes impossible for molecules, owing to the complex, polycentric nature of the potential field. However, approximate methods have provided many results of interest, and provided a real insight into a number of complicated phenomena. One of these methods is based on the assumption that in the neighborhood of a given atom A, the wave function most appropriate for describing the behavior of an electron is ψ_A, where ψ_A is an atomic orbital of A. The approximate wave function for the whole molecule is then

$$\psi = a\psi_A + b\psi_B + c\psi_C \ldots\ldots$$

that is, the sum of the atomic orbitals taken over all the atoms in the molecule, weighted with appropriate coefficients. Having assumed this function as a molecular orbital, the central task of the method becomes one of determining the values of the coefficients. This approximation is called the LCAO method (linear combination of atomic orbitals). The method will be illustrated for the hydrogen molecule-ion, which is the simplest molecule, consisting of two protons and one electron: $(H \cdot H)^+$ (3).

In this case, the proper wave functions to employ in the LCAO are the hydrogen atom wave functions, ψ_A and ψ_B. These functions are solutions of the Schrödinger equation with $V = -e^2/r$. The molecular orbital is

$$\psi = a\psi_A + b\psi_B \tag{5}$$

The use of equation (5) is justified as follows: for large distances of the electron from the nuclei, ψ_A and ψ_B approach zero. When the electron is in the region of A, the molecular orbital ψ will resemble ψ_A since the distance of the electron from nucleus B will be relatively large. Our approximate function ψ will deviate from the best approximation to the extent that ψ_B actually departs from zero under these conditions. From equation (5) and the fact that the nuclei are alike, it can be shown that the two linearly independent wave functions for the hydrogen molecule-ion are given by:

$$\begin{aligned} \psi_I &= c(\psi_A + \psi_B) \\ \psi_{II} &= c(\psi_A - \psi_B) \end{aligned} \tag{6}$$

where c is a constant. Referring to the Schrödinger equation (4), we will let:

$$H = -\frac{h^2}{8\pi^2 m}\nabla^2 + V(q) \tag{7}$$

where H is called the Hamiltonian for the system specified by the potential function $V(q)$. Then the Schrödinger equation appears simply as:

$$H\psi = E\psi \tag{8}$$

where E is the energy of the system. Multiplying equation (8) from the left (H is a differential operator, and the meaning of multiplication is preserved only if performed from the left), integrating over all values of the coordinates q, and solving for E, we find:

$$E = \frac{\int \psi H \psi d\tau}{\int \psi^2 d\tau} \tag{9}$$

Substitution of the expression for ψ_I in this equation gives:

$$E = \frac{H_{AA} + \beta}{1 + S} \tag{10}$$

where $H_{AA} = \int \psi_A H \psi_A d\tau = H_{BB}$, β = resonance integral $= \int \psi_A H \psi_B d\tau = \int \psi_B H \psi_A d\tau$, and S = overlap integral $= \int \psi_A \psi_B d\tau$. The equality of the expressions for H_{AA} and H_{BB} and of the two resonance integrals is a result of the symmetry of the problem. By substitution of the hydrogen wave functions (of the 1*s* type) into the expressions for β and S, it can be shown that β is negative and S is positive. Further, when the

electron is in the region of nucleus A, to a first approximation, $H \sim H_A$, where H_A is the Hamiltonian for the hydrogen atom. Hence, in accord with equation (9):

$$E_A = \frac{\int \psi_A H_A \psi_A d\tau}{\int \psi_A^2 d\tau} \sim \frac{\int \psi_A H \psi_A d\tau}{\int \psi_A^2 d\tau} = \frac{H_{AA}}{\int \psi_A^2 d\tau} \tag{11}$$

where E_A is the energy of the electron associated with a single positive nucleus. Now ψ_A, which is an exact solution of the Schrödinger equation for the hydrogen atom, can be so chosen that $\int \psi_A^2 d\tau = 1$. Therefore,

$$E_A \sim H_{AA}$$

and from (10):

$$E \sim \frac{E_A + \beta}{1 + S} \tag{12}$$

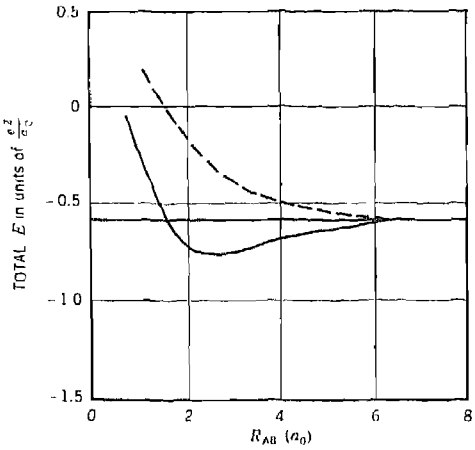


Fig. 5. Energy diagram for bonding (solid curve) and antibonding (broken curve) states of the hydrogen molecule-ion (3). The atomic parameter a_0 has a value of about 0.53 A.; e is the electronic charge.

Since β is less than zero and S is greater than zero, E is less than E_A. The calculation shows that the energy, E, of the electron is lower when the electron is associated with two hydrogen nuclei than when it is associated with one nucleus (where its energy is then E_A). Consequently, bonding can be said to have occurred. The integral S is a measure of the extent to which the hydrogen-like orbitals of atoms A and B overlap to form the molecular orbital. According to equation (12), the greater the amount of overlap, the lower E will be, and hence the greater will be the binding energy. The strongest bonds are therefore formed from atomic orbitals that can overlap most effectively in the molecular orbital. A calculation of electron density using the molecular orbital resulting from overlap in the hydrogen molecule-ion shows that the electron spends most of its time between the two nuclei. The occupation by an electron of a molecular orbital composed of two overlapping atomic orbitals is analogous to Lewis' concept of a shared or covalent bond, since, in such a molecular orbital, the electron belongs to two atoms jointly. The concentration of the electron between the nuclei corresponds to Lewis' procedure of indicating the existence of a bond joining two atoms by means of dots between them.

The resonance integral, β, corresponds roughly to an oscillation of the electron between the two nuclei, but has in fact no immediate physical significance. The substitution of actual wave functions into the energy expression (10) gives the energy E as a function of the internuclear distance R_{AB}. The addition of the Coulombic repulsion, e^2/R_{AB} to E gives the total energy of the hydrogen molecule-ion as a function of R_{AB}. A plot of this function is given by the solid curve in Figure 5. The minimum in this curve corresponds to formation of a stable molecule. The hydrogen

molecule-ion has been observed spectroscopically in the excitation of the hydrogen molecule. Although the calculation just given yields rather crude results, refinements on the method (for example, choosing more complicated wave functions than 1*s* atomic orbitals) have given results in complete agreement with experiment.

A similar calculation of the energy of the system using ψ_{II} (eq. 6) leads to a value of $E > E_A$; that is, no bonding occurs, since the energy of the electron in this molecular orbital is higher than when it is in the atomic orbital E_A. An energy diagram (dotted curve, Fig. 5) shows that ψ_{II} leads to repulsion of the nuclei at all distances R_{AB} and a calculation of the electron distribution shows that the electron is repelled from the region between the nuclei. For this reason, ψ_{II} is called an *antibonding orbital*; ψ_I is called a *bonding orbital*. It is possible for electrons in a stable molecule to be in antibonding states, and they must often be placed in such states to avoid conflict with the Pauli exclusion principle. In such cases, the molecule is stable because the *total energy of the bonding orbitals exceeds the total destabilization due to the occupation* of antibonding orbitals.

In general, the form of a molecular orbital for a diatomic molecule is taken as:

$$\psi = \psi_A + \lambda\psi_B \tag{13}$$

where λ is a constant, and ψ_A and ψ_B are orbitals of the atoms in the molecule. For a molecule in which the bond is produced by an electron pair, the orbital given by equation (13) will be occupied by two electrons having opposed spins. No more than two such electrons can occupy this orbital, or the exclusion principle would be violated. In this manner, the Pauli exclusion principle preserves the fundamental significance of the electron pair originally ascribed to it by Lewis. The case where $\lambda = \pm 1$ corresponds to a homonuclear diatomic molecule such as H_2, O_2, etc. In such molecules, there is no net displacement of the electronic charge toward either atom, and such molecules are nonpolar. For cases where simple single bonds are involved, as in H_2, the bond is called "pure covalent."

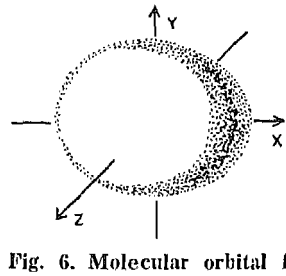


Fig. 6. Molecular orbital for the hydrogen molecule (13a). This orbital is composed of two 1*s* atomic orbitals.

If $\lambda > 1$, ψ_B will be more important, and ψ will have more of the character of ψ_B. The electrons in the bond will tend to become concentrated around atom B, and the bond will be polar. This occurs when atoms of unequal electron-attracting capabilities form a bond, as in HCl. The unsymmetrical charge distribution leads to a dipole moment. Where λ becomes very large indeed, ψ is best represented by ψ_B alone, and both electrons may be assigned to the atomic orbital belonging to B. This corresponds to ionization of the molecule A—B, and the transition to an electrovalent bond.

The shapes of the molecular orbitals that result from the LCAO treatment depend upon the shapes of the component atomic orbitals, and the way in which these orbitals are oriented in the molecule. In the hydrogen molecule, the 1*s* orbitals overlap to give a molecular orbital which is symmetrical about the bond axis (see Fig. 6). Owing to its symmetry, such a bond is called a sigma (σ) bond. This terminology has no reference to the kinds of atomic orbitals that make up the molecular orbital. Thus, two p_x atomic orbitals could overlap to form sigma bonds, and the central bond in hydrazine, $H_2N—NH_2$, is of this type; that is, the electrons are in a molecular orbital which is symmetrical about the bond axis. However, another type of bond,

called the pi (π) bond, is also possible, and an analysis of the bonding in the nitrogen molecule will serve to show the nature of the latter kind of bonding.

The electron distribution of a nitrogen atom is $1s^2 2s^2 2p_x^1 2p_y^1 2p_z^1$. In forming the nitrogen molecule, three $2p$ electrons are available for bond formation at each atom. The two $2s$ electrons on each atom remain in these very stable orbitals, and appear as unshared electron pairs that do not contribute to bonding (in fact, it can be shown that one pair of these electrons appears in a bonding molecular orbital and the other

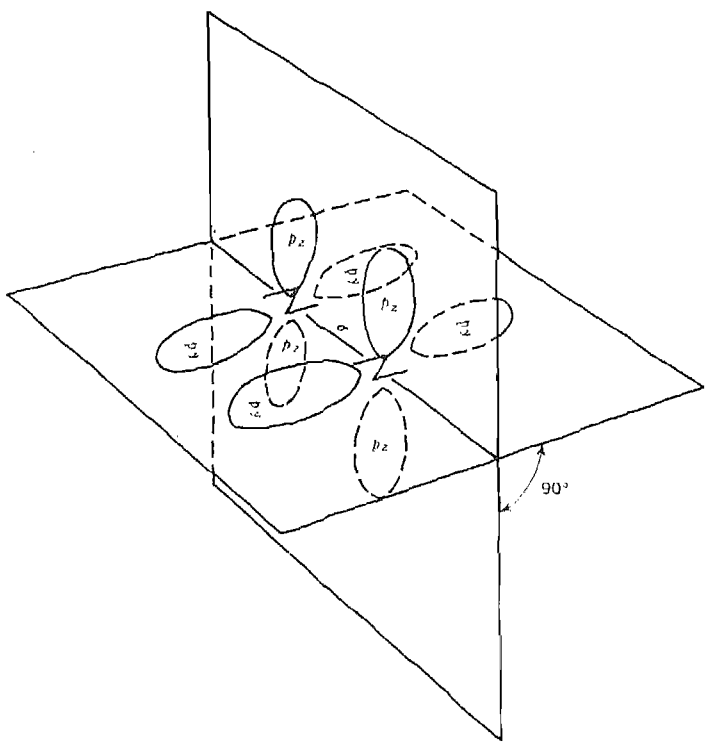


Fig. 7a. Molecular skeleton of the nitrogen molecule. This shows the sigma bond formed by p_x-p_x overlap, and the alignment of p_y and p_z atomic orbitals prior to overlap to form pi molecular orbitals.

pair in an antibonding orbital, so that their contributions cancel) (3). The $2p_x$ orbitals on each atom can form a molecular orbital by overlap, which will accommodate both $2p_x$ electrons with opposed spins. This corresponds to formation of a sigma bond. With formation of this bond, the $2p_y$ and $2p_z$ orbitals can be aligned in pairs in a parallel manner, as shown in Figure 7a, and these orbitals can overlap in pairs to form two molecular orbitals (see Fig. 7b). One of these molecular orbitals extends above and below the bond axis in the z-direction; the other molecular orbital extends at right angles to the latter orbital. Each of these molecular orbitals can accommodate two electrons with opposed spins. The molecular orbitals formed from the p_z and p_y orbitals in this manner each have a node along the bond axis, corresponding to zero probability that electrons in these orbitals will be found along the bond axis. Orbitals of this kind are designated as *pi orbitals*. In the nitrogen molecule, therefore, the

atoms are joined by one sigma bond and two pi bonds, which corresponds to the classical formula : N≡≡N : .

It is clear from the above discussion that the character of the bonds occurring in a molecule depends upon the kinds of atomic orbitals that contribute to the molecular orbitals. Which atomic orbitals are involved in bonding depends upon the electronic states assumed by the atoms undergoing combination. Such an electronic state is often called a *valence state*. The valence state of an atom may often differ from the electronic state described in the periodic table. Our previous discussion indicated, for example, that the electronic configuration of the carbon atom should be $1s^2 2s^2 2p_x^1 2p_y^1$, which predicates a valence of two for carbon. This is not in accord with the fact that the usual valence of this element is four. The required tetravalence of carbon would appear if one of the $2s$ electrons were promoted to the vacant $2p_z$ orbital: $1s^2 2s^1 2p_x^1 2p_y^1 2p_z^1$. The possible existence of this state has been confirmed by spectroscopic studies, which also show that this valence state is 96 kg.-cal./mole above the normal $1s^2 2s^2 2p^2$ state. Nevertheless, two more bonds are possible from the promoted state than from the normal state, and the large gain in bonding energy more than compensates for the energy required to reach the promoted state. However, the valence state of carbon is not completely settled by this argument. Overlap of the atomic orbitals from the promoted state with hydrogen $1s$ orbitals would yield three C—H bonds at mutual right angles (involving the three perpendicular $2p$ orbitals) and one undirected valence (involving the $2s$ orbital). However, in methane, the bonds are known to be directed toward the corners of a tetrahedron. If, instead of using these elementary atomic orbitals for overlap, linear combinations of them are employed, the tetrahedral nature of the carbon atom appears. Since there are four orbitals, four linearly independent combinations:

Fig. 7b. Molecular orbitals in the nitrogen molecule.

$$\psi_i = a_i s + b_i p_x + c_i p_y + d_i p_z, \qquad i = 1,2,3,4$$

are possible. When this is done, and the coefficients of the expanded wave function have been determined (15), it is found that these four orbitals form angles of 109°28′ to each other. Any atomic orbital which is derived from a mixture of elementary atomic orbitals is called a *hybridized orbital*. In the example just given, the four orbitals are called sp^3 hybrids. The four hybridized orbitals now replace the original s and p orbitals, and bonding to other atoms occurs through overlap of these hybridized orbitals with orbitals from those atoms.

Confusion between the processes of hybridizing atomic orbitals and forming molecular orbitals is possible, since each involves taking linear combinations of atomic orbitals. The hybrid orbital is composed of atomic orbitals associated with the same atom. The molecular orbital is made up of atomic orbitals associated with different atoms.

Hybridization has another consequence, which is at least as important as the preservation of the correct stereochemistry: bonds formed from such orbitals are stronger than those formed from the elementary orbitals. Bond strength, which is the amount of energy required to separate completely two atoms participating in a bond, is determined by the extent to which two atomic orbitals can overlap to form a molecular orbital. This in turn depends upon the extension of the atomic orbitals

into space. In Figure 8 is shown the projection of an sp^3 hybrid orbital (solid curve) on which is superimposed for comparison purposes the projection of a p orbital (broken curve); the nucleus of the atom is to be imagined at the origin. Since the hybridized orbital has greater extension into space than the p orbital, to a first approximation, overlap with another atomic orbital is more efficient for the hybridized orbital.

There are other ways in which the atomic orbitals of the carbon atom can be hybridized, and these lead to different valence states. Hybridization of a $2s$ orbital with p_x and p_y orbitals, the sp^2 hybrid, gives three coplanar orbitals of equal bonding strength, directed at 120° to each other. Three of the four valence electrons can go into these three orbitals; the fourth electron remains in the $2p_z$ orbital. The spatial distribution of these orbitals is shown in Figure 9a. Since the hybrid receives contributions from p_x and p_y orbitals, the plane of the hybrid must be the xy-plane; the p_z orbital is therefore perpendicular to the plane of the sp^2 hybrid. In Figure 9b is shown the consequence of hybridization of an s and a p_x orbital: two linearly independent combinations of these two orbitals are possible, giving hybrid orbitals that are collinear and oppositely directed. The p_z and p_y orbitals, which were not utilized in hybridization, remain perpendicular to each other, and to the line of the sp hybrid.

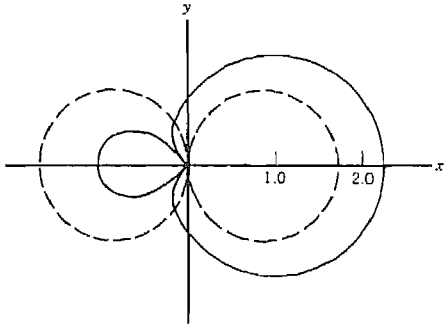


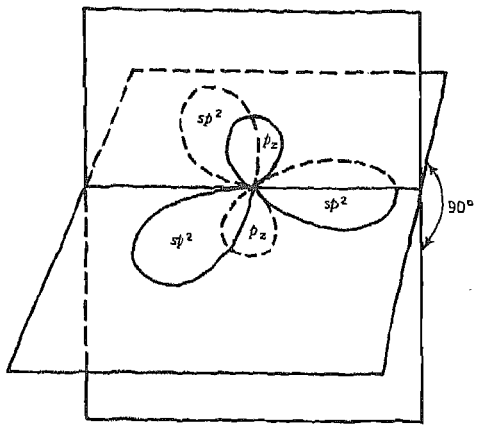
Fig. 8. Comparison of an sp^3 hybrid (solid curve) and a p orbital (broken curve). The actual shape of the orbitals is obtained by rotating these curves about the x-axis.

The valence states of two carbon atoms at a double bond can be considered to arise from sp^2 hybridization. Using ethylene as an example, a molecular orbital can be formed by overlap of hybrid sp^2 atomic orbitals, one from each carbon atom. Occupation of this molecular orbital by two electrons with opposed spins gives a sigma bond. Two more sigma bonds can be formed from each carbon atom by overlap of pairs of sp^2 hybrids with $1s$ orbitals from hydrogen atoms. This establishes the basic molecular skeleton and sigma bond system (see Fig. 10a). At each carbon atom there remains a p_z orbital occupied by one electron. These p_z orbitals can overlap by becoming oriented in a parallel manner, and the resulting pi orbital can be occupied by the two p_z electrons. The distribution of bonds is shown in Figure 10b. Because the p_z orbitals become parallel in order to form the pi-molecular orbital, and because of the coplanarity of the three sp^2 hybridized bonds, the ethylene molecule as a whole must be coplanar. Furthermore, in order to twist the carbon atoms relative to each other, the pi bond must be broken. This energy barrier prevents free rotation, which accounts for the existence of isolable cis and trans isomers. Since the overlap of the p_z orbitals is smaller than overlap of atomic orbitals in sigma orbitals, the electrons in the pi orbital are less constrained than those in sigma orbitals, and this high mobility of the electrons in a pi bond accounts for the unsaturated character of olefins.

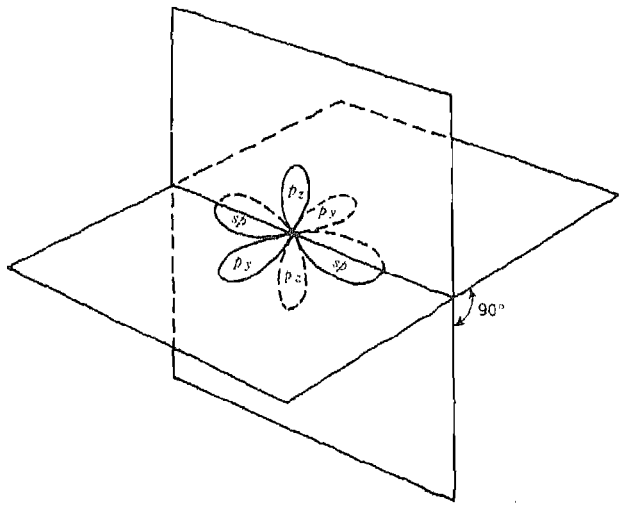
In acetylene, a sigma bond can be formed between the carbon atoms by overlap of one sp hybrid orbital from each carbon atom. The remaining sp orbitals are used in sigma-bond formation with hydrogen atoms. The remaining electrons are in p_y and p_z orbitals, which overlap in pairs to form two pi orbitals. Because of the nature

of the component orbitals, these two pi orbitals are at right angles, and have nodes in the bond axis (see Fig. 10c).

Hybridization may occur in elements other than carbon. The electronic state of oxygen is $1s^2 2s^2 2p_x^2 2p_y^1 2p_z^1$. Bonding from this state can occur by overlap of the singly occupied p_y and p_z orbitals with other atomic orbitals. The theoretical bond angle around the oxygen atom is therefore 90°. The observed bond angle in water



(a)

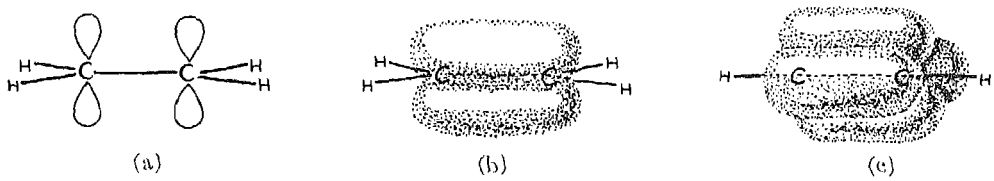


(b)

Fig. 9. Distribution of orbitals about a carbon atom. (a) In an sp^2 hybrid state; (b) in an sp hybrid state.

is 105°. This has been accounted for in terms of repulsions between the hydrogen nuclei, which constitute positive ends of dipoles. It appears that this repulsion is not sufficient to account wholly for the spread of the bond angle, and a certain amount of hybridization involving the 2*s* orbital exists to give "partial" sp^2 hybrids (3). The nitrogen atom, with the electronic configuration $1s^2 2s^2 2p_x^1 2p_y^1 2p_z^1$ may bond with three hydrogen atoms to form ammonia. The bond angle will be 90° if only the *p* orbitals

are involved, the unshared electron pair remaining in the 2*s* orbital. As in the case of water, the bond angle is spread to 105°, and likewise, the spreading is attributed to a combination of interatomic repulsions and a small amount of sp^3 hybridization. When ammonia forms a salt, $NH_4^+X^-$, all four bonds in the ammonium ion become equivalent and the valence state changes from one involving *p* orbitals with a small amount of



(a) (b) (c)

Fig. 10. (a) Molecular skeleton of ethylene showing p_z atomic orbitals prior to overlap. (b) Ethylene, showing the pi electron bond. (c) Distribution of the two pi electron bonds in acetylene (13a).

sp^3 character to one involving four sp^3 hybrids. The tetrahedral nature of the ammonium nitrogen atom has been confirmed by the isolation of optically active forms of asymmetric quaternary ammonium salts, $RR'R''R'''N^+X^-$ (see *Stereochemistry (organic)*). With the formation of the fourth bond, the covalence of nitrogen becomes saturated, since further bonding must involve the high energy 3*s* orbital.

In phosphorus, which has an outer shell similar to nitrogen, $3s^23p^3$, tricovalency occurs as in phosphine, PH_3, or the phosphorus trihalides, PX_3. Like nitrogen, phosphorus can also show tetracovalency, as in the ion $[PCl_4]^+$, which is present in crystals of PCl_5. Unlike nitrogen, phosphorus can also show pentacovalency, as in PF_5. As implied above, it is doubtful that phosphorus is pentavalent in PCl_5, which appears to be ionic in character. In the case of PF_5, a 3*d* orbital is probably utilized for formation of the fifth covalent bond, since the energy separating the 3*d* and 3*p* orbitals is much less than that separating the 2*p* and 3*s* orbitals in nitrogen, where pentacovalence was said to be impossible. The initial bonding state in phosphorus pentafluoride is probably $3s^13p_x^13p_y^13p_z^13d^1$; that is, a 3*s* electron is promoted to the 3*d* level. Hybridization of the five singly occupied orbitals gives five equivalent orbitals arranged in a trigonal bipyramid, so that PF_5 has the configuration shown in Figure 11, with three coplanar P—F bonds forming angles of 120°, and two collinear P—F bonds perpendicular to the plane of the first three (22). The case of phosphorus illustrates one source of the variable valence exhibited by elements of higher atomic number. Differences in the energies of subshells with higher values of *l* (*p*, *d*, *f*, . . . shells) become less as *n* increases. For this reason, promotion of electrons from lower filled levels to higher unoccupied levels (as in phosphorus) occurs more readily with increasing *n*. Consequently, elements after the first two rows of the periodic table are more likely to show a number of different valences, and variable valence becomes the rule rather than the exception.

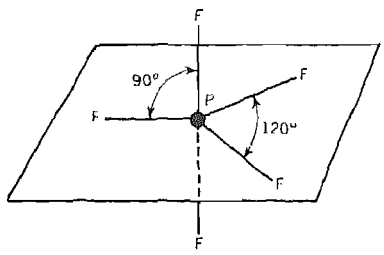


Fig. 11. Spatial distribution of bonds in PF_5.

Boron, with the normal configuration $1s^22s^22p_x^1$, can assume the valence state $1s^22s^12p_x^12p_y^1$, from which it will form bonds using sp^2 hybrids. Thus BF_3 is a planar molecule with a bond angle of 120°. Boron trifluoride can coordinate with another

fluoride ion to form BF_4^-, and in so doing, boron attains the noble gas configuration. The additional electron pair might be expected to go into the vacant p_z orbital of the boron atom, but the presence of the added pair permits sp^3 hybridization to occur, and the BF_4^- ion is tetrahedral. Ammonia and boron trifluoride, each of which can attain more stable bonding states by donating or receiving electron pairs respectively, are simple examples of a base and an acid, according to Lewis' general definition (see *Acid-base systems*).

An alternative approach to the application of quantum mechanics to molecules is embodied in the valence bond, or VB, method (15,16). The VB method combines atomic orbitals in a somewhat different way than the molecular orbital method, although both yield the same results in the highest approximations. If two widely separated atoms A and B each have associated with them electrons 1 and 2, respectively, it can be shown that the wave function for this sytem of noninteracting atoms is $\psi_A(1)\psi_B(2)$ where the first factor is the wave function of electron 1 around nucleus A, and the second factor is the wave function of electron 2 around nucleus B. It is now assumed that the product form of the wave function for this system is preserved as the atoms A and B approach each other, and begin to interact. A calculation of the energy shows that for infinite separation, $E = E_A + E_B$, but that E decreases as the internuclear distance decreases. However, since the wave function for the system of isolated atoms is rather a poor approximation to the actual wave function when the atoms are close enough to interact, the calculated value of E remains much larger than the experimental value. On the other hand if a term corresponding to exchange of the electrons between the nuclei is added to the wave function, so that:

$$\psi = \psi_A(1)\psi_B(2) + \psi_A(2)\psi_B(1) \tag{14}$$

a much better value of E is obtained. The two terms in equation (14) arise from the fact that we cannot distinguish between the two electrons. Even better accord with the observed value of E is obtained if terms such as $\psi_A(1)\psi_A(2)$ and $\psi_B(1)\psi_B(2)$ are added to the wave function. These latter terms correspond to structures in which both electrons appear on one nucleus, and hence represent ionic structures. The two terms appearing in equation (14), taken together, represent a purely covalent structure. The correspondence between terms and structures is:

A:B	A:$^-$B$^+$	A$^+$:B$^-$
$\psi_A(1)\psi_B(2) + \psi_A(2)\psi_B(1)$	$\psi_A(1)\psi_A(2)$	$\psi_B(1)\psi_B(2)$

These observations imply that a calculation of the energy of a molecule in which only covalent structures are considered is likely to lead to results that do not agree with experiment. Furthermore, the electronic configuration of a molecule is poorly represented by the classical valence bond structures, and other (ionic) structures must also be taken into account. This does not imply that the electron distribution in the molecule AB corresponds to any one of the structures given above, but rather that the electronic distribution is an average of all three structures. This is a restatement of the well-known **resonance principle:** if several structures can be written for a molecule that differ only in the distribution of electrons, then the actual electron distribution will not correspond to any of these structures, but will be a combination of all of them. A molecule that can be represented in this manner is called a *resonance hybrid.*

In order to obtain the most general expression for the wave function of the molecule A:B in valence bond terms, equation (14) must be modified to read:

$$\psi = c_1[\psi_A(1)\psi_B(2) + \psi_A(2)\psi_B(1)] + c_2\psi_A(1)\psi_A(2) + c_3\psi_B(1)\psi_B(2) \qquad (15)$$

where c_1, c_2, and c_3 are constants. The squares of these coefficients are roughly proportional to the "percentage contribution" which the corresponding terms make to the wave function. Analogously, the squares of these coefficients are roughly proportional to the percentage contribution that the corresponding structures make to the resonance hybrid. The magnitude of these coefficients (and hence their squares) is related to the stability of the various contributing structures: structures that are energetically more favored will be represented with relatively larger coefficients in equation (15). For example, in hydrogen chloride, the chlorine atom, owing to its high electronegativity relative to hydrogen, will have a greater attraction for electrons. Thus the structure H^+Cl^- is energetically more favored than H^-Cl^+, and the ionic term $\psi_{Cl}(1)\psi_{Cl}(2)$ would have a much larger coefficient in the wave function than $\psi_H(1)\psi_H(2)$. Consequently, the wave function for this molecule is best approximated by:

$$\psi_{HCl} = c_1[\psi_H(1)\psi_{Cl}(2) + \psi_H(2)\psi_{Cl}(1)] + c_2\psi_{Cl}(1)\psi_{Cl}(2) \qquad (16)$$

where, owing to the relative smallness of its coefficient, the term which assigns both electrons to the hydrogen atom has been omitted. In these terms, the structure of hydrogen chloride is represented as:

$$H{-}Cl \longleftrightarrow H^+Cl^-$$

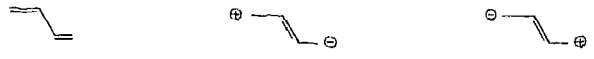
where the double-headed arrow indicates that the actual electron distribution is intermediate between the extreme structures. On this basis, granting the importance of contributions of the ionic state in HCl, the polar nature of the bond is accounted for. In general, polarity of a bond in valence bond language is ascribed to contributions of ionic structures to the resonance hybrid. If such ionic structures cancel in the hybrid, the molecule will be nonpolar; in the hydrogen molecule, which can be represented as follows:

$$H^+H^- \longleftrightarrow H{-}H \longleftrightarrow H^-H^+$$

the contributions of the ionic structures cancel: these two structures are equal in energy, and make equal contributions. The characteristic of polar molecules is that oppositely polarized structures do not make equal contributions, owing to energy differences in the structures, as discussed above.

The comparison of the molecular orbital and valence bond treatments of the polar single bond is instructive. In the molecular orbital treatment, it is assumed initially that the orbital is distorted in such a way that electrons have a tendency to accumulate on one atom. No superposition of structures appears here, because this result was obtained by increasing the relative size of the coefficient of one of the contributing atomic orbitals in the LCAO. In the valence bond treatment, the contributing ionic structure appears, but the effect of adding this structure, as equation (16) shows, is to weight the orbital toward the more electronegative atom. In the final analysis, therefore, these two methods give quite similar wave functions.

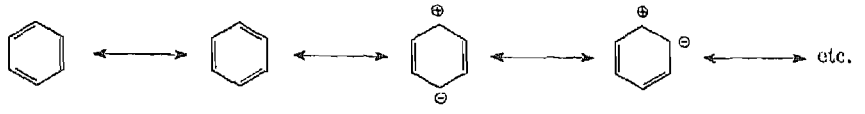
The concept of resonance reaches its greatest qualitative utility in application to molecules (particularly organic molecules) which contain double bonds, especially conjugated double bonds (15,30). For the simplest conjugated olefin, butadiene, the following structures can be written:



(XIIa) (XIIb) (XIIc)

According to the resonance principle, the electronic distribution in this molecule must be an average of all three of these structures. Accordingly, the central bond in butadiene must have a certain amount of double bond character. This is borne out by electron diffraction data, which show that this bond is somewhat shorter (1.46 A.) than a normal C—C bond (1.54 A.), having shifted in the direction of the length of a carbon-carbon double bond, which is 1.34 A. in ethylene. The tendency for a double bond to form at the center of the molecule is closely related to the occurrence of 1,4-addition. It is remarkable that the distribution of bonds given by this modern picture is very close in some respects to that pictured by Thiele in 1899, as described earlier.

The structure of benzene is best represented as a hybrid of the two covalent structures proposed originally by Kekulé, and of a number of ionic structures:



Because the ionic structures involve charge separation, and are therefore high in energy content, they will make relatively minor contributions; in fact, the contribution of the two Kekulé structures is about 80%. There is a great deal of physical and chemical evidence supporting the electron distribution in benzene as described by resonance. Although the structure of benzene is commonly written with double bonds, the substance itself shows few of the characteristic properties of olefins and undergoes substitution rather than addition. The bond distance between neighboring carbon atoms is 1.39 A., and is uniform around the ring. This bond distance corresponds to that of neither a single nor a double bond, and the fact that all bond distances are equal shows that benzene cannot even be approximated by one classical structure. The heat of formation of benzene is also anomalously high, and this supports the nonclassical distribution of electrons prescribed by resonance theory, as the following argument shows.

From tables of bond energies, computed from thermochemical data for simple compounds such as methane and ethylene, it is possible to calculate the heat of formation of benzene, assuming that it consists of three C=C, three C—C, and six C—H bonds. Although this type of calculation gives quite accurate results for nonresonating molecules, in the case of benzene the calculated heat of formation is about 40 kg.-cal./mole too high, which is well beyond experimental error. It is clear that such a deviation between computed and measured values might have been expected, since we have indicated that the classical structure of benzene, which is the basis for the calculation, does not correspond exactly to the actual electron distribution. The deviation between the heat of formation as calculated from bond energies for classical structures, and the observed heat of formation is called the *resonance energy*. This quantity is a measure of the extra stability conferred upon a molecule as the result of resonance. In quantum mechanics, resonance energy appears as the amount by which the energy E of equation (9) is lowered as terms corresponding to the various resonance structures are introduced into the approximate wave function (see p. 569). The justification for the carrying over of the mathematical operation of adding terms to the wave function

into the operation of superimposing resonance structures is based on a theorem the proof of which can be found in Pauling's book (16); the energy of a molecule calculated from equation (9) can never be lower than the observed value, provided that the correct Hamiltonian (H) has been chosen. For a given H, the best wave function is one that minimizes E. The fact that inclusion of several structures into the calculation of the energy of benzene leads to a lower value of the molecular energy implies that the actual structure of benzene is not the classical one, but is better represented as a resonance hybrid.

The preceding analysis serves as a qualitative justification for the resonance principle. However, a closer analysis shows, oddly enough, that the calculated value of E converges more rapidly to the observed value than the approximate wave function converges to the actual wave function. In other words, values of E calculated from equation (9) tend to be more accurate than the wave functions used in obtaining them.

(a) (b) (c) (d)

Fig. 12. (a) Distribution of p_z atomic orbitals in benzene prior to overlap. (b), (c) Two different ways of combining the p_z atomic orbitals in pairs to form pi molecular orbitals. These structures correspond to the classical structures of benzene (13a). **(d) The six-component pi molecular orbital** (13b).

For this reason, the electron distribution which is obtained from the approximate wave function is more likely to be in error than the value of the energy corresponding to the superposition of states dictated by the approximation. This is the reason the use of the resonance principle is attended with the requirement that all possible likely electronic structures be included in the resonance hybrid, although even the use of this requirement does not guarantee a fully accurate representation of the true electron distribution in a molecule.

The application of the molecular orbital approximation to benzene leads to a picture of the electron distribution that is analogous to that discussed above. The valence state of a carbon atom in benzene is that of an sp^2 hybrid (this is also true in the resonance treatment). The sigma bonds in the ring are formed by overlap of pairs of these orbitals. The remaining sp^2 hybrids (one at each carbon atom) are used to form sigma bonds to hydrogen atoms. As shown in Figure 12a, p_z orbitals, each containing one electron, are left at each carbon atom. There are several ways in which pi orbitals may be formed from these p_z orbitals. Two ways are shown in Figures 12b and 12c, in which adjacent pairs of p_z orbitals have formed molecular orbitals containing two pi electrons. These structures correspond to the Kekulé structures for benzene. The wave function for such a combination of atomic orbitals would be $c_1\psi_1 + c_2\psi_2$, and there would be three such (molecular) orbitals for structures shown in Figures 12b or 12c. However, alternative orbitals are possible; namely, those of the form $c_1\psi_1 + c_2\psi_2 + c_3\psi_3 + c_4\psi_4 + c_5\psi_5 + c_6\psi_6$: that is, molecular orbitals to which all six p_z orbitals around the ring contribute. Calculation shows that the total energy of six electrons in three of these molecular orbitals is lower than that of six electrons in the three two-component molecular orbitals, which comprise a Kekulé structure. The

electron distribution corresponding to the six-component molecular orbital is pictured in Figure 12d. Molecular orbital theory predicts that the delocalized orbital will lead to a more stable molecule than either of the structures in Figure 12b or 12c. The difference in energy between the delocalized molecular orbital, and the three localized, two-component molecular orbitals is called, appropriately, the *delocalization energy*. Obviously, delocalization energy and resonance energy are analogous. The picture of electron distribution provided by this treatment is essentially that given by the valence bond resonance treatment.

The concept of resonance is not a necessary adjunct to chemistry, nor a necessary outgrowth of quantum mechanics. In molecular orbital theory, for example, no notion related to resonance occurs. Both valence bond and molecular orbital treatments give pictures of electron distributions in molecules which in some cases (for example, benzene) are quite different from the classical ones. Molecular orbital treatment ascribes this to a difference between the orbitals implicit in classical assumptions and those that actually exist within the molecule. This necessarily leads to pictures of electron distributions that are nonclassical. Resonance theory, on the other hand, recognizes the utility of classical structures as a convenient, and often accurate, symbolism, and seeks to amend inadequacies in classical representations in terms of the superposition of a number of classical structures. It is not surprising, therefore, that the greatest qualitative application of quantum mechanics to chemistry has been made in terms of the resonance hypothesis, since this hypothesis does the least apparent violence to traditional structures which are deeply established in chemistry. On the other hand, the situation is reversed in the quantitative application of quantum mechanics to complex molecules. Here the molecular orbital treatment is somewhat more easily managed than the valence bond (resonance) treatment.

Groups that possess unshared electron pairs, when attached to an aromatic ring, or to an atom participating in a double bond, show interaction with the pi electron cloud. In resonance language, the structure of vinyl chloride, for example, is best represented as a resonance hybrid:

$$\underset{\text{(XIIIa)}}{CH_2{=}CH{-}Cl} \qquad \underset{\text{(XIIIb)}}{\overset{(-)}{C}H_2{-}CH{=}\overset{(+)}{C}l} \qquad \underset{\text{(XIIIc)}}{CH_2{=}\overset{(+)}{C}H\overset{(-)}{C}l}$$

Resonance between structures (XIIIa) and (XIIIc) constitutes the normal resonance present in a molecule such as ethyl chloride, according to which the electrons in the C—Cl bond are, on an average, displaced toward the chlorine atom. On this basis, since ethylene itself has zero dipole moment, the dipole moment of vinyl chloride might be expected to be the same as that of ethyl chloride (2.05 Debyes). However, contributions of structure (XIIIb) produce a charge separation which is in opposition to that of structure (XIIIc), and lowers the moment of vinyl chloride relative to ethyl chloride to a value of 1.44 Debye units. A similar situation exists in chlorobenzene, whose dipole moment (1.92 Debyes) is lower than that of cyclohexyl chloride (2.07 Debyes), owing to contributions to resonance of ionic structures such as the following:

As a result of such resonance, the C—Cl bond in each of these examples must be con-

sidered to have a certain amount of double-bond character. This is supported by bond distance measurements: the normal C—Cl distance is 1.77 A.; in chlorobenzene and vinyl chloride, the C—Cl distance is 1.69 A. This theory of interaction of substituents with pi electrons has assumed great importance in the theory of aromatic substitution, and the properties of substituted aromatic nuclei (5,29).

Bibliography

(1) Bohr, N., *The Theory of Spectra and Atomic Constitution*, Cambridge Univ. Press, London, 1922.
(2) Brown, G. I., *A Simple Guide to Modern Valency Theory*, Longmans, Green, N.Y., 1953.
(3) Coulson, C. A., *Valence*, Oxford Univ. Press, London, 1952.
(4) de L. Kronig, R., *The Optical Basis of Chemical Valence*, Cambridge Univ. Press, London, 1935.
(5) Dewar, M. J. S., *The Electronic Theory of Organic Chemistry*, Oxford Univ. Press, London, 1949.
(6) Eyring, H., Walter, J., and Kimball, G. E., *Quantum Chemistry*, Wiley, N.Y., 1944.
(7) Ferguson, L. N., *Electron Structures of Organic Molecules*, Prentice-Hall, N.Y., 1952.
(8) Ketelaar, J. A. A., *Chemical Constitution*, Elsevier, Houston, Tex., and Amsterdam, 1953.
(8a) Klyne, W., *Progress in Stereochemistry*, Vol. I,, Academic Press, N. Y., 1954.
(9) Lewis, G. N., *Valence and the Structure of Atoms and Molecules*, Chemical Catalog Co., N.Y., 1923.
(10) Mackle, H., "The Evolution of Valence Theory and Bond Symbolism," *J. Chem. Educ.*, **31**, 618 (1954).
(11) Mills, W. H., "The Basis of Stereochemistry," *J. Chem. Soc.*, **1942**, 457.
(12) Moeller, T., *Inorganic Chemistry, An Advanced Textbook*, Wiley, N.Y., 1952.
(13) Muir, M. M. P., *History of Chemical Theories and Laws*, Wiley, N.Y., 1909.
(13a) Noller, C. R., *J. Chem. Educ.*, **27**, 505 (1950).
(13b) Noller, C. R., *J. Chem. Educ.*, **32**, 23 (1955).
(14) Palmer, W. G., *Valency: Classical and Modern*, Cambridge Univ. Press, London, 1946.
(15) Pauling, L., *The Nature of the Chemical Bond*, Cornell Univ. Press, Ithaca, N.Y., 1940.
(16) Pauling, L., and Wilson, E. B., *Introduction to Quantum Mechanics*, McGraw-Hill, N.Y., 1935.
(17) Penney, W. G., *Quantum Theory of Valency*, Methuen, London, 1935.
(18) Pitzer, K. S., *Quantum Chemistry*, Prentice-Hall, N.Y., 1953.
(19) Rây, P., *The Theory of Valency and the Structure of Chemical Compounds*, Eka Press, Calcutta, 1946.
(20) Remick, A. E., *Electronic Interpretations of Organic Chemistry*, 2nd ed., Wiley, N.Y., 1949.
(21) Rice, O. K., *Electronic Structure and Chemical Binding*, McGraw-Hill, N.Y., 1940.
(22) Sidgwick, N. V., *The Chemical Elements and Their Compounds*, Oxford Univ. Press, London, 1950.
(23) Sidgwick, N. V., *The Covalent Link in Chemistry*, Cornell Univ. Press, Ithaca, N.Y., 1933.
(24) Sidgwick, N. V., *The Electronic Theory of Valency*, Oxford Univ. Press, London, 1927.
(25) Slater, J. C., *Quantum Theory of Matter*, McGraw-Hill, N.Y., 1951.
(26) Sugden, S., *The Parachor and Valency*, George Routledge and Sons, London, 1930.
(27) Syrkin, Y. K., and Dyatkina, M. E., *Structure of Molecules and the Chemical Bond*, trans. M. A. Partridge and D. O. Jordan, Interscience, N.Y.-London, 1950.
(28) Waters, W. A., *Physical Aspects of Organic Chemistry*, 4th ed., Van Nostrand, N.Y., 1950.
(29) Wheland, G. W., *Advanced Organic Chemistry*, 2nd ed., Wiley, N.Y., 1949.
(30) Wheland, G. W., *The Theory of Resonance*, Wiley, N.Y., 1944.
(31) Wheland, G. W., *Resonance in Organic Chemistry*, Wiley, N. Y., 1955.

JOHN FIGUERAS, JR., AND R. L. BENT

VALENTINITE, Sb_2O_3. See *Antimony and antimony alloys*, Vol. **2**, pp. 52, 53.

VALERALDEHYDE, $CH_3(CH_2)_3CHO$. See *Aldehydes*, Vol. **1**, p. 336.

VALERIC ACID, $CH_3(CH_2)_3COOH$. See *Fatty acids*, Vol. **6**, pp. 174, 248.

VALEROIDINE, $C_{13}H_{23}NO_3$. See *Alkaloids*, Vol. **1**, p. 480.

VALERONITRILE, $CH_3(CH_2)_3CN$. See *Nitriles and isocyanides*, Vol. **9**, p. 354.

VALINE, $(CH_3)_2CHCH(NH_2)COOH$. See *Amino acids*, Vol. **1**, pp. 719, 720.

VALONIA. See *Tanning materials*, Vol. **13**, pp. 581, 583, 585.

VALVES. See *Pipes and valves*, Vol. **10**, p. 714; *Pressure technique*, Vol. **11**, p. 111.

VANADATES. See *Vanadium compounds*.

VANADIUM AND VANADIUM ALLOYS

Vanadium, V, atomic number 23, atomic weight 50.95, belongs to group V in the periodic system in the subgroup that contains niobium (columbium, *q.v.*) and tantalum; it is between titanium and chromium horizontally. Six isotopes have been found, covering the range of atomic weights 47–52. Vanadium is a gray-colored metal, soft in the pure state, crystallizing in the body-centered cubic system. Mineral sources are principally the more or less oxidized and altered sulfide ores occurring in the Peruvian Andes, and the equally complex minerals of the Colorado Plateau, including carnotite, roscoelite, and others of lesser industrial importance.

Vanadium was first discovered in 1801 by M. del Rio in a Mexican lead ore. He named the element "erythronium," but described it inadequately. When the discovery was challenged, del Rio accepted the explanation that erythronium was merely an impure chromium. In 1830, N. G. Sefstroem isolated a new metal from slags of iron-smelting operations at Taberg, Sweden. Because of the beautiful colors of its salts, he named the element vanadium, in honor of the Norse goddess of beauty, Freya Vanadis. In the same year, Woehler was able to show that erythronium and vanadium were identical. During the 19th century, Berzelius and Roscoe worked extensively on the chemistry of the element.

At the turn of the century, Moissan, Hélouis, Arnold, and also Sankey and Smith pioneered the use of vanadium in steel.

Commercial development of vanadium followed the metallurgical studies (principally in ferrous metallurgy) of Choubley (1896), Hélouis (1897), Arnold (1900), and Guillet (1904). This work resulted in armor plate of superior resistance, in tool steels of greatly improved cutting capacity as well as wear-resistance, and in a substantial increase in useful strength (that is, elastic limit, yield strength, etc.) of constructional steels, without sacrifice of toughness. More recently, Marden and Rich (1927), Gregory, and McKechnie and Seybolt (1950), and others have been active in the production of pure vanadium metal (4,8,9).

Properties

Owing to the great affinity of vanadium for oxygen, carbon, and nitrogen, it is extremely difficult to produce the metal in the pure state. For that reason, the physical constants have only recently been rather precisely determined and they may still be subject to some modification.

M.p., 1710 ± 25°C.; b.p., 3000°C.; sp.gr., 6.11; sp.heat, 20–100°C., 0.12 cal./(gram)(°C.); linear coefficient of thermal expansion, 20–720°C., $9.7 \pm 0.3 \times 10^{-6}$/°C; thermal conductivity, to 100°C., 0.074 cal./(sec.)(sq.cm.)(°C./cm.); electrical resistance, at 20°C., 24.8 microhm-cm.; hardness, annealed, 76 Rockwell B.

High-purity vanadium is very stable. The metal has a remarkable resistance to non-oxidizing acids, sea water, etc. It is, however, attacked by oxidizing acids. Va-

nadium oxidizes rapidly at over 675°C. The metal also combines readily with nitrogen and with carbon to form nitrides and carbides. For methods of analysis see *Vanadium compounds.*

Occurrence

Just about the time when the usefulness of vanadium as an alloying element for steel began to be recognized, Riza Patron discovered in 1905 the first large deposit of rich vanadium ore in the Peruvian Andes. Previously small amounts of vanadium had been obtained from Spanish and Swedish sources. This new deposit, the Mina Ragra, at an altitude of 16,000 ft., responded to the demand of industry at a critical moment, and provided the bulk of world requirements of vanadium for many years.

The element is widely distributed throughout the lithosphere, but at a low concentration, which has been estimated at 0.07% of the lithosphere.

The current production of molybdenum and tungsten is substantially greater than that of vanadium, but this is due in part to the high degree of dissemination of vanadium and the limited number of deposits of high concentration and large volume. Vanadium is a constituent in granites and other igneous as well as sedimentary rocks, as a replacement element in the minerals, where it takes the position of iron, tin, aluminum, and phosphorus, depending on its valence. It is thus generally a concomitant element in iron and titanium ores, bauxite, and phosphate rocks. It occurs in iron ores from mere traces up to occasionally more than 1%. Such ores are found in many regions, among others in Scandinavia, France (minette ores of Lorraine), India, Japan, Chile, Canada, and the United States (Adirondack Region).

Its wide distribution may be one of the reasons for the importance that vanadium has in biology. It occurs in the blood of holothurians, ascidians, and other aquatic life. Sea water is said to contain about 0.3 gram of vanadium per thousand cubic meter. The beet root, the vine, the beech, and the oak also contain traces of the element. The occurrence of vanadium in the ashes of coals, oils, and asphalts reflects this biological concentrating action.

Vanadium has also been detected in meteorites and in the spectrum of numerous stars as well as that of the sun.

Ores

The most important sources of the metal are the sulfides—oxidized to a major or minor extent—and vanadates of the Peruvian Andes, the carnotite-roscoelite ores of the Colorado Plateau ("four state" area), the lead-zinc-copper-vanadates which occur particularly in southern Africa, and to a lesser degree the chlorovanadates of Mexico and the southwestern U.S.

More than 65 vanadium minerals have been described (2,3). All but 5 or 6 are of secondary origin, formed during oxidation or weathering. The primary minerals are:

(*1*) Patronite, $V_2S_5 + nS$—found only at Mina Ragra, Peru, the largest known vanadium deposit. It is a greenish-black amorphous mineral, usually carrying some iron, nickel, molybdenum, phosphorus, and carbon.

(*2*) Bravoite, $(Fe,Ni,Co,V)S_2$—found in small quantities at Mina Ragra. Brassy cubes of metallic luster with 25% Fe, 15% Ni, 5% V, sometimes Co, 45% S.

(*3*) Sulvanite, $3Cu_2S \cdot V_2S_5$—found in Burra-Burra, South Australia, and in Utah. Bronze-yellow crystals containing 51% Cu, 14% V, 35% S.

(*4*) Davidite—found at Mt. Painter, South Australia. A vanadium bearing titanium-iron mineral.

(*5*) Roscoelite, $K(V,Al)_2(AlSi_3)O_{10}(OH,F)_2$—found in a number of rich gold-bearing veins, and importantly as a secondary mineral in the Colorado and Utah sandstones. A micaceous mineral containing 20% V_2O_5, 7.5% K_2O, 14% Al_2O_3, 2% MgO, 1.5% FeO, 47.5% SiO_2.

(*6*) Montroseite, (V,Fe)O(OH).

These primary minerals have been widely altered as they were affected by the oxidizing action of the upper lithosphere. The following is a regional listing of the principal vanadium minerals.

Metallic veins of Mexico, New Mexico, Arizona, Nevada, Argentina, Spain, Turkestan, South West Africa, and Rhodesia carry some of the following minerals: vanadinite, $Pb_5(VO_4)_3Cl$; descloizite, $Pb(Zn,Cu)VO_4(OH)$; mottramite (cuprodescloizite, psittacinite), $Pb(Cu,Zn)VO_4(OH)$.

Mineral deposit of Peru: hewettite, $CaO.3V_2O_5.9H_2O$; melanovanadite, $2CaO.2V_2O_4.3V_2O_5$; pascoite, $2CaO.3V_2O_5.11H_2O$.

Uranium-bearing sandstones of Colorado, Utah, and Arizona: carnotite, $K_2O.2UO_3.V_2O_5.3H_2O$; tyuyamunite, $Ca(UO_2)_2(VO_4).5\text{–}9H_2O$; roscoelite; hewettite, $CaO.3V_2O_5.9H_2O$; volborthite, $Cu_3(UO_4)_2.3H_2O$; ferganite, $2Fe_2O_3.2V_2O_5.5H_2O$; rossite, $CaO.V_2O_5.4H_2O$; montroseite; rauvite, $CaO.2UO_3.5V_2O_5.16H_2O$(?).

Fergana valley (Central Asia), Turkestan: tyuyamunite; volborthite.

Where vanadium is mined, it usually occurs in a number of associated minerals, as indicated in the foregoing. Groups of minerals are concentrated and treated together.

TABLE I. Vanadium Ore Production in Metric Tons of Vanadium Content.

	Country				
	Peru	U.S.A.	Northern Rhodesia	South West Africa	
	Principal ore				
Year	Patronite	Carnotite and roscoelite[a]	Pb-Zn-Cu vanadates		World production[b]
1940	1214	981	368	428	3024
1942	1010	2014	388	453	2014
1944	514	1600	254	385	2757
1946	322	577	68	430	1403
1948	511	Not available	173	187	Not available
1950	436	Not available	—	295	Not available
1951	449	Not available	87	529	Not available
1952	450	Not available	43	624	Not available
1953	—	Not available			

[a] And vanadiferous sandstone.
[b] Exclusive of Russia.

Statistics of vanadium production have been deficient during the early period and in recent years clothed in secrecy, as far as carnotite production is concerned. Peruvian production reached a maximum with 1214 metric tons of contained vanadium in 1940; U.S. production was reported at a maximum of 2534 metric tons in 1943; Northern Rhodesia and South West Africa had their respective production peaks in 1929 with 565 metric tons and 1921 with 650 metric tons of contained vanadium.

Current trends are indicated by Table I which is based on U.S. Bureau of Mines data.

In addition to mine-product sources of vanadium, by-products yield supplies of moderate importance. There are vanadium-bearing slags obtained in the bessemerizing of vanadium-containing pig iron or from open-hearth slags produced in the refining of such irons. Other vanadium-rich by-products are produced in the reduction of the complex copper-lead-zinc vanadates which occur with other minerals of these metals. A small percentage of the total vanadium marketed is obtained from the combined soot and ash deposited in the tubes of Scotch-type marine boilers, as well as from slags formed in many types of boiler settings. It is necessary, of course, that the fuel oil be of relatively high vanadium content, as are the oils of Venezuela. Recovery of vanadium from such sources is practiced more widely in Europe than in the U.S. Small amounts of vanadium are recovered also in the processing of phosphate rock during the production of fertilizers.

Over 90% of the vanadium produced is consumed in the steel industry, where the metal is used in the form of ferrovanadium. Only about 5% of the available supply is consumed in the form of vanadium chemicals and by a large variety of industries. Small quantities are used by the nonferrous metal industry.

Extraction

Vanadium is most generally extracted from its principal ores and by-product sources by roasting with common salt to sodium vanadate which is leached out with water. The residue may be leached again with dilute sulfuric acid yielding a combined extract which can be precipitated with sulfuric acid, in various manners, to obtain an oxide concentrate. This product is commercially known as "vanadium pentoxide," and ordinarily analyzes over 80 per cent V_2O_5, although it may carry enough Na_2O and/or CaO to be actually a sodium and/or calcium hexavanadate. When such concentrates are redissolved in a soda solution and maintained in the pentavalent state, the addition of ammonium chloride will precipitate ammonium metavanadate, NH_4VO_3. This white crystalline powder may again be calcined to give a pure vanadium pentoxide suitable for reduction to vanadium metal.

PRODUCTION OF VANADIUM ALLOYS

Reduction of vanadium from ores, slags, chemically produced compounds such as V_2O_5, etc., is accomplished with carbon, with silicon, or with aluminum. The practice employed depends in part on the product desired and its intended use. The products ordinarily carry between 35 and 80% vanadium along with differing amounts of other elements, more particularly excess of the reducing agent, the balance being iron. Very small quantities of more or less pure vanadium metal are also being made. Table II shows compositions of the various grades of ferrovanadium and vanadium.

Reduction with Carbon. Carbon, the cheapest reducing agent, is very difficult to adapt for use in the reduction of vanadium pentoxide or other vanadium-containing materials, as it is difficult to keep the metal low in carbon, while lower oxides may be formed that are resistant to reduction. The principle then is that of heating the furnace charge to such a temperature and so manipulating it that the reduction of the pentoxide proceeds directly to the metallic stage without formation of intermediate compounds. This has been accomplished by conducting the reduction in a narrow zone with a high energy input. Here the metal is produced, forms droplets, and

TABLE II. Ferrovanadium and Vanadium, Grades, Cost, and Compositions.

Designation	Reduction method	Composition, % V	Si	C	Fe	Al	Cost,[a] $/lb. contained vanadium
Iron foundry grade	C, Si, or Al	32–42	7–11	1 (approx.)	Bal.	—	3.00
Grade A (Open hearth)	C, Si, or Al	50–55	7.5 max.	3 max.	Bal.	1.5 max.	3.00
Grade B (Crucible)	C, Si, or Al	50–55 70–80	3.5 max.	0.5 max.	Bal.	1.5 max.	3.10
Grade C (Primos)	Al	50–55 70–80	1.25 max.	0.2 max.	Bal.	1.2 max.	3.20
Vanadium metal, 90%	Al	91.15	0.5	0.17	Bal.	2.25	3.50
Vanadium metal, 99.7% min.	See p. 588	99.7	0.05	0.1	—	—	65.00

[a] June 1, 1954.

rapidly sinks through the surrounding slag and unreacted material to the metal pool at the bottom of the furnace. Thus, undesirable secondary reactions are avoided.

The design resulting from this concept is a relatively high furnace space of narrow, rectangular cross section with water-cooled roof and electrode openings. The 4000-kw. furnace has a power input of 190 kw./sq.ft. of hearth area. Electrodes are arranged in line and create a high-energy reduction zone where they dip through the charge into the slag. This zone is fed automatically with a well-mixed charge of small particle size, consisting of roasted ore, coke, steel scrap, and fluxes. Tapping of metal and slag is intermittent and separate. The slag, being closer to the reaction zone, is hotter than the metal. The ferroalloy produced has the following approximate composition: 33–42% V, 3–5% Si, 3–3.5% C, or 35–40% V, 8–12% Si, 2–3% C, balance being Fe in either case.

Reduction with Silicon. Low-carbon vanadium alloys can be produced via a silicon-bearing primary alloy from which the silicon is removed by reaction with vanadium pentoxide in a second step. Since the difference in the heat of reaction between silicon and vanadium in the formation of oxides is not very substantial, the reaction end-point is reached only sluggishly and incompletely in the secondary refining step.

Vanadium pentoxide concentrates, usually of carnotite-roscoelite origin, are worked by this process. The operation is approximately as follows: a mixture of pentoxide, 90% grade ferrosilicon, lime, and some fluorspar is smelted in an electric furnace lined with magnesite. The primary metal produced contains about 30% V, while the slag carries 0.4–0.9% V. The primary metal is refined with vanadium pentoxide and lime in a second step, and the secondary slag is returned as part of the charge to produce primary metal.

It is also possible to produce a high-silicon and low-carbon vanadium-silicon alloy by smelting vanadium pentoxide, silica, coke, and fluxes. After grinding the primary alloy together with vanadium pentoxide, the mixture is caused to react to produce ferrovanadium. This process can be modified in detail in many ways but is generally practiced in the electric furnace with application of considerable electric energy.

Reduction with Aluminum. Aluminothermy is the oldest process for the production of ferrovanadium. Although aluminum is generally a more expensive reducing agent, the process does not require an electric furnace and the high cost of the reducing

agent is relatively unimportant by comparison with the cost of the vanadium pentoxide concentrate. The process gives a relatively pure product with a high vanadium content, and the yield is good.

Originally, aluminum reduction was conducted by producing a relatively low-vanadium alloy, starting with an iron vanadate. Later vanadium pentoxide was used, and made possible the production of richer alloys with 40% or 50% or 80% V. As the process is now practiced, the reaction mixture consists of vanadium pentoxide, aluminum, iron punchings, and fluxes, such as calcium fluoride. This mixture is ignited by a charge containing barium dioxide and aluminum to create the threshold temperature of 1730°F. The reaction is performed in a furnace or crucible without the addition of external heat other than a mild preheating of the lining. The furnace can be disassembled to remove the reaction products, or the refractory lining of the metal shell forming the crucible can be broken away.

The extremely violent reaction—energy developed is the equivalent of 1000 kw./sq.ft. of hearth area—is balanced by adjusting the particle size of all reagents and the rate of feeding the charge, by working with partially prereduced material, or by replacing aluminum in part with a less active reducing agent such as calcium carbide, silicon, or carbon. There are a multitude of factors that must be attuned to operate consistently and satisfactorily.

In a standard operation 2 tons of raw materials are fed into a 14-cu.ft. crucible to complete the reaction in one hour, producing 1 ton of 40% ferrovanadium and 1 ton of slag without raising the temperature above 2800°F., generating the heat equivalent of 3200 kw. The yield improves with the volume of the operation, as heat losses decline and as the period during which the products are liquid is extended. Under proper operating conditions there is a clean separation of metal and slag. Purity of the ferrovanadium depends on the raw materials employed since impurities find their way almost entirely into the regulus.

PRODUCTION OF PURE METAL

Marden and Rich in 1927 reduced vanadium pentoxide with calcium:

$$V_2O_5 + 5\,Ca \longrightarrow 5\,CaO + 2\,V$$

and added calcium chloride, on an equimolar basis with the calcium, to flux the lime produced. Since 1950, these earlier experimental production methods have been adapted to the small-scale production of high-purity vanadium. Gregory and Lilliendahl (4) introduced the modification of using vanadium trioxide, V_2O_3 (produced by hydrogen reduction of the pentoxide) to lessen the heat of the reaction. McKechnie and Seybolt (9) further improved the process by substituting iodine for the calcium chloride, at the rate of first 0.1, later 0.2 mole per mole of vanadium produced. This gives a slag with different properties from which the metal collects as a solid regulus instead of droplets.

Each of the producers have developed their own bomb design based on this work. Reguli are reported to be up to about 15 lb. of metal. In the pure metal, traces of carbon, nitrogen, and oxygen have a profound effect on mechanical properties, as they lead to hardness and embrittlement when present substantially in excess of about 0.1% C plus 0.01% N plus 0.025% O. Producers state the following composition limits for commercial metal: 99.7–99.9% V, 0.03–0.11% C, 0.02–0.10% N, 0.027–0.10% O, 0.002–0.04% H.

Experimental work continues on the van Arkel-de Boer method, thermal decomposition of vanadium iodide on a hot wire. The process is not at present economic, but it may lead to vanadium of still greater purity. Electrolysis in molten salt baths protected by a nonreactive atmosphere is also being studied.

Uses

Vanadium plays a most important part in the steel industry as an alloying element. The Fe-V system clearly resembles the Fe-Cr system; in both cases there is complete liquid solubility throughout the binary system, there is a gamma-loop restricting the existence of austenite, and likewise an intermetallic compound, FeU, at 50 atom per cent. The addition of carbon to the system is technologically important, as vanadium forms a very hard and stable carbide, V_4C_3, in carbon and most low-alloy steels. In the higher-alloy steels, the relationships are more complex and multiple carbides containing more than one metal are believed to exist. In low-vanadium, low-carbon steels, the vanadium is apparently present principally in the iron matrix, but it is increasingly present as carbide as the proportions of carbon and/or vanadium to iron increase.

As a carbide former, vanadium is stronger than tungsten and chromium, but in order to derive the optimum value from vanadium additions to a given steel, hardening practice must be modified to permit the vanadium carbide to go into solution in substantial quantity in the austenite. Complete solution of the carbide is undesirable since, at the temperatures at which this occurs, grain refinement (a most important attribute of vanadium steels) may be lost. Quenching locks the carbide in the ground mass, and tempering within a suitable temperature range permits it to precipitate to form finely disseminated, hard carbide particles of very small size.

An interesting application of the influence of solution of vanadium carbides is evident in the behavior of low-alloy vanadium tool steels. Steels in this category, having a high-carbon content and a low-vanadium content (up to about ¼%) have a hard surface and a tough core, while higher-vanadium bearing steels may be caused to develop excellent deep-hardening qualities, if quenching temperatures are suitably adjusted, by raising to a higher level for maximum hardness penetration.

It is still not entirely clear whether a relationship actually exists between the formation of fine nuclei of vanadium carbide—and perhaps nitride—and the fine grain engendered in the steel as a result of vanadium addition. Certainly the dual effects of relatively small additions of vanadium to steel, namely grain size control and the high degree of dispersion of hard carbides, have had a profound effect on steel quality and therefore steel metallurgy. The resistance to grain growth of vanadium-bearing steels in effect widens controllably the heat-treatment temperature range and is very advantageous in large castings and forgings.

Vanadium in Steel Production and Processing. Although vanadium combines with oxygen and with nitrogen in steel, it is not a "scavenger" or a commercially useful deoxidizing agent as ordinarily understood, as it does not reduce the active contents of these two gases to the low levels that can be secured by, for example, aluminum and boron. There are, however, cases where the effects accompanying deoxidation by aluminum are objectionable, and also cases where the type of product is completely altered by aluminum deoxidation. Thus vanadium is used for its oxygen-combining power (without aluminum) in heavy forgings requiring high transverse ductility;

also, and presumably for its nitrogen-combining power, it is extensively employed in rimming steels. In most cases, however, vanadium is not added to steel until there has been previous effective deoxidation so that there is either no loss of vanadium in making alloy steels or very little loss, normally under 10%.

In **tool steels** there is full application of the properties discussed above, resulting from the incorporation of vanadium. Thus the control of grain size in carbon and very low-alloy tool steels secures an assured depth of hardening which is effectively utilized in taps and dies. The resistance to grain growth at heat-treatment temperatures improves the handling of tools of varying section, and the stability of the carbide permits the application of higher tempering temperatures to provide improved shock resistance at high hardness. The ability to retain the carbides in effective form accounts also for improved cutting performance in edge tools and tools of other types in which wear resistance is a requisite.

The composition and uses of some vanadium tool steels are shown in Vol. **12,** pp. 824–25.

In the U.S. the most common high-speed tool steel was originally of the 18–4–1 (tungsten-chromium-vanadium) type. For special uses other types and compositions are employed, occasionally with lower tungsten and higher vanadium (14–4–2). For the very highest wear resistance, carbon and vanadium are simultaneously increased to as high as 1.5 and 5.0% respectively. Cobalt in the range of 3–12% has been added to the matrix, that is, in replacement of iron. Molybdenum has been used in these high-speed tool steels in varying degree, sometimes as 1 or 2% added to the above 18–4–1 type, and sometimes substituting for a large part or almost all of the tungsten; invariably this substitution appears to require an increase in vanadium to maintain cutting capacity, etc., as evidenced in one composition, 6–6–4–2 (W-Mo-Cr-V), which now dominates the U.S. market. As indicated above, the carbon content must always be higher as the vanadium content increases, regardless of the remainder of the composition, if the full effectiveness of the vanadium addition is to be assured. However, where high-speed tools are required to sustain very severe impact loads, carbon is kept as low as possible. Except in the high-vanadium types (over 2% V), carbon content of the high-speed steels will range between 0.65 and 0.85%.

Vanadium in Wrought Constructional Steels. Most frequently it is desirable and economical in the application of alloy constructional steels to subject either bars, plates, forgings, or finished parts made from them to a quenching and tempering heat treatment, thereby developing maximum strength properties. Vanadium improves the useful strength in steels of this class at any given level of maximum strength or hardness, or, expressed differently, it improves the ratio of yield strength to tensile strength. This effect applies equally to simple carbon-vanadium steels, and to the more complex alloy types wherein vanadium is associated with one or more of nickel, chromium, molybdenum, or manganese in the range of 1–2% or even more.

The properties developed by quenching and tempering result from the presence of highly dispersed vanadium carbides and from the control of fine grain size which at least in large part is due to the presence of discrete particles of the carbide. The yield ratio noted above, as well as the ultimate strength developed by quenching, is dependent upon the time the steel is held at the quenching temperature and the temperature itself (within limits), rising as these factors increase; thus, these properties increase as more carbide is taken into solution. However, if the practice is carried undesirably far, subsequent tempering will cause these carbides to precipitate at grain

boundaries, and this results in a decrease in impact strength from the very high levels that result from quenching at usual temperatures. Therefore a desired balance may be secured by adjustment between these heat-treating conditions, the steel composition and its ultimate use.

Normalizing is also frequently applied in industrial practice to large sections with or without tempering, inasmuch as desired strength levels may be obtained while retaining fine grain size and high resistance to impact. Heat treatment of this type also guards against distortion both in fabrication and use, accounting for the application of these steels to various types of axles and shafts for heavy machinery.

In lighter machine elements, such as parts for automotive equipment, aircraft, and machine tools, quenched and tempered chromium-vanadium steels of the SAE-6100 series are frequently encountered. Examples are shafts, gears, propeller blades, and leaf and coil springs. Table III presents a summary of the most important types of wrought constructional vanadium steels.

In **cast steels,** the above principles are likewise applied, while additionally the limiting effect of vanadium upon the growth of dendrites following solidification offers further advantages. This latter feature is of distinct aid in the casting operation itself as well as during subsequent heating and cooling in the course of heat treatment.

Although many vanadium cast steels are subject to quenching and tempering to develop the desired final properties, much use is made, as in the case of heavy forgings, of normalizing and tempering because of the excellent mechanical properties resulting from this heat treatment when applied to steel compositions suitably selected for the intended use. Many composition variants are employed, the vanadium ordinarily ranging from about 0.05 up to about 0.20% with the carbon content for cast constructional steels varying from about 0.20 up to about 0.50%, and in conjunction with nickel or chromium or manganese or one or more of these with molybdenum also included. Typical steel casting compositions are the following: (*1*) 0.35% C, 0.2% V for locomotive frames, heavy gears, housings; (*2*) 1.5% Mn, 0.1% V for heavy transportation equipment; (*3*) 1.5% Ni, 0.1% V for heavy equipment dies; (*4*) 1% Cr, 1% Mo, 0.2% V for large turbine castings.

For **high-temperature steels,** the stability of the vanadium carbides in the tempering temperature range (which is also the usual range of applications) is highly important, as are also the properties resulting from a deliberate coarsening of the grain and taking practically all of the carbide into solution.

In this class of uses involving tubes, plates, bolts, fittings, etc., are found steels ranging from 0.2 to 0.5% carbon and 0.2 to 0.4% vanadium, combined with other carbide forming elements, namely molybdenum over the range of about 0.3–1.0%, chromium in the range of 0.5–2%, and sometimes tungsten within the limits of about 1–2.5%.

Since the late 1940's, a special steel has been developed for steam generation and transmission at temperatures of up to 1100°F. or slightly higher, which contains 1% Cr, 1% Mo, and 0.25% V. This steel has had a very good service record in spite of its relatively low alloy content. Maximum service ability seems to have resulted from solution of the carbides, in that the steel is used after normalizing from a temperature of at least 1900°F.

In **cast irons,** vanadium is only occasionally used as the single alloying element, much greater use being made of the element in amounts between 0.05 and 0.20%, associated with one or more of nickel, molybdenum, chromium, and copper. Va-

TABLE III. Vanadium Constructional Steels, Compositions for Uses.

Type	Analysis, %				Uses	Remarks
	C	Mn	V			
C–V	0.35–0.55	0.6–1.0	0.10–0.20		RR equipment, shafts, arms, connecting rods, driving axles, crank pins, guides, piston rods. Also parts for heavy machinery, pumps, diesel engines.	Fine grain and high impact resistance, with simple heat treatment, normalizing and tempering.
	C	Mn	V	Cr		
Cr–V	0.1–1.0	0.3–1.0	0.05–0.50	0.4–1.2	Low carbon: carburized gears, camshafts, piston pins. Pressure vessels, tubing. Stampings.	Adapted to various hardening practices.
					Medium carbon: axles, shafts, steering arms, gears, springs. Arbors, spindles, shafting. Cyanided gears, bolts, washers, forgings.	High useful strength with toughness.
					High carbon: tools, ball bearings, wearing plates.	Wear resistance and adaptable depth of hardness.
	C	Mn	V			
Mn–V	0.10–0.35	1.0–1.5	0.05–0.20		Heavy forgings, plates for transportation equipment and for tanks. Also for rivets, bolts, etc.	Normalized and tempered forgings of large cross section with high strength, ductility, and impact resistance. Also high fatigue strength under alternating stresses.
	C	Mn	V	Cr		
V-spring steels	0.5–0.7	0.6–0.9	0.08–0.2	0.4–1.0	Heavy and light springs for transportation equipment and heavy machinery apparatus and instruments. Automotive springs.	Proven long life under most severe operating conditions.

nadium tends to limit graphitization and aids in effecting uniform graphite distribution and the production of graphite flakes of moderate size. It hardens the iron and assists in the production of uniform strength and hardness in heavy sections, while at the same time improving resistance to wear and permitting service at moderately elevated temperatures. Used with other alloying elements and suitable inoculating agents, excellent strength levels and desirable microstructure for machining, etc., may be developed over a wide range of cross sections. Typical compositions and uses are as follows: (*1*) 0.7% Ni, 0.3% Cr, 0.5% Mo, 0.1% V for diesel cylinder heads; (*2*) 0.5% Mo, 0.4% Cr, 0.1% V for die blocks; (*3*) 1.5% Ni, 0.2% V for machine tool ways; (*4*) 1.5% Cu, 0.1% V for brake drums.

Nonferrous uses of vanadium are at present limited. Through the medium of a copper-vanadium alloy of about 3% vanadium content, the element has been used to a limited degree for the control of gases and microstructure in a number of copper-base alloys. It has also been added along with either silicon or nickel as a means of effecting desired thermal expansion rates combined with good strength properties in aluminum alloy pistons in internal combustion engines.

The availability of pure vanadium is now leading to alloys of high vanadium content, as for example in association with titanium, while aluminum-reduced vanadium of low iron content is being used to produce vanadium-rich aluminum-vanadium alloys. These special compositions give promise of substantial application in high-temperature service.

Bibliography

(1) Dunn, H. E., "Manufacture of Ferro-Vanadium," *Vancoram Rev.*, **1**, 73–78 (1930).
(2) Franklin, F. F., "The Vanadium Minerals. I," *Vancoram Rev.*, **6**, No. 2, 11–15 (1949).
(3) Franklin, F. F., "Vanadium Minerals," *Vancoram Rev.*, **6**, No. 4, 10–17 (1949).
(4) Gregory, E. D., and Lilliendahl, W. C., "Production of Ductile Vanadium by Calcium Reduction of Vanadium Trioxide," *J. Electrochem. Soc.*, **98**, 395 (1951).
(5) Hampel, C. A. (ed.), *Rare Metals Handbook*, Reinhold, N.Y., 1954, pp. 573–602.
(6) Houdremont, E., *Sonderstahlkunde*, Springer, Berlin, 1935, p. 356.
(7) Kinzel, A. B., "Vanadium Metal—a New Article of Commerce," *Metal Progress*, **58**, 315 (1950).
(8) Marden, J. W., and Rich, M. N., "Vanadium," *Ind. Eng. Chem.*, **19**, 786–88 (1927).
(9) McKechnie, R. K., and Seybolt, A. V., "Preparation of Ductile Vanadium by Calcium Reduction," *J. Electrochem. Soc.*, **97**, 311 (1950).
(10) Pearson, W. B., "Vanadium and its Alloys," *J. Iron Steel Inst.*, **164**, 149–59 (1950).
(11) Van Arkel, A. E., *Reine Metalle*, Springer, Berlin, 1939, p. 220.
(12) *Vanadium Steels and Irons*, Vanadium Corp. of America, N.Y.
(13) Weeks, A. D., and Thompson, M. E., "Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateaus," *U.S. Geol. Survey, Bull.*, **1009-B**, 62 pp. (1954).

JEROME STRAUSS

VANADIUM COMPOUNDS

The chemistry of vanadium is exceedingly complex, because (*1*) it has numerous valence states, at least four, +2, +3, +4, and +5, being well defined, (*2*) it is amphoteric (though predominantly basic in the lower oxidation states, acidic in the higher), (*3*) it forms derivatives from more or less well-defined radicals, such as VO^{2+} and VO^{3+}, (*4*) its oxygen acids readily form condensed acids. Table I presents in outline form a comparison of the oxidation states of vanadium.

The nomenclature of vanadium compounds is subject to much confusion. In U.S. industrial practice, the oxidation states +2 to +5 are often called, respectively, hypovanadous, vanadous, hypovanadic and vanadic, but these terms have also been applied differently. For example, the +2 oxidation state has been described as "vanadous." In U.S. industrial practice "vanadyl" refers to VO^{2+}, thus vanadyl chloride, $VOCl_2$, vanadyl sulfate, $VOSO_4$, but some writers have used "vanadyl" for the group VO with different valences, and refer to $VOCl_2$ and $VOCl_3$ as vanadyl dichloride and vanadyl trichloride. Ambiguity is avoided by the names vanadium oxydichloride and oxytrichloride. Among the oxysalts, the names "vanadite" and "hypovanadate" have been used synonymously for those of oxidation state +4. The use of Stock numerals is very helpful, as vanadates(IV), or vanadium(III) oxide, V_2O_3.

TABLE I. Comparison of the Oxidation States of Vanadium.

Oxidation state	Oxide	Other compounds	Typical color in aqueous solution	Remarks
1?	V_2O?	—	—	Doubtful
2	VO, basic	$V(OH)_2$, VCl_2, VSO_4	Yellow to green	Powerful reducing agents; often isomorphous with compounds of Fe^{2+}, Cr^{2+}, Mg^{2+}
3	V_2O_3	$V(OH)_3$, VCl_3, $VOCl$, V_2S_3, VN	Green	Reducing agents; often isomorphous with compounds of Fe^{2+}, Cr^{3+}, Al^{3+}; form alums and complex cyanides and thiocyanates
4	VO_2, basic	VCl_4, $VOCl_2$, $VOSO_4$	Blue	—
	weakly acidic	$Na_2V_4O_9$	Black	—
5	V_2O_5, weakly basic	VF_5, $VOCl_3$	Yellow to red	—
	acidic	$NaVO_3$, $Na_4V_2O_7$, Na_3VO_4, and others	Pale yellow to yellow	Most stable and best known
—	—	$(NH_4)_2VO_4$, $NH_4H_2V_2O_2$	Yellow to orange	Obtained by action of H_2O_2

The oxidation-reduction potentials relating the various valence states are (*7*):

	Volts
$V \rightarrow V^{2+} + 2e$	+1.5
$V^{2+} \rightarrow V^{3+} + e$	+0.2
$V^{3+} + H_2O \rightarrow VO^{2+} + 2H^+ + e$	−0.314
$VO^{2+} + 3H_2O \rightarrow V(OH)_4^+ + 2H^+ + e$	−1.00

Vanadium(II) compounds are very strong reducing agents, but they can be dissolved in water without reducing it at room temperature. Vanadium compounds are fairly easily oxidized to the +4 state, and by powerful oxidizing agents to the +5 state. Vanadates in neutral solution are not easily reduced, but in acid solution Fe^{2+} gives VO^{2+}, Sn^{2+} gives V^{3+}, and Zn gives V^{2+} (7). Many vanadium salts readily dissociate on heating in air, forming vanadium pentoxide, V_2O_5, and all vanadium compounds will produce vanadates(V) on alkaline fusion in air.

The only vanadium compounds that are regular articles of commerce are the pentoxide, V_2O_5, and ammonium metavanadate, NH_4VO_3, which are prepared in various grades of purity according to the demand. The price of commercial quantities of ammonium metavanadate was $1.75 in 1954, and had been at that level for a number of years.

Analysis. A delicate test for vanadate is the addition of tannin, which yields a rich blue coloration in concentrations down to 2 mg. of vanadium pentoxide equivalent per liter. The color of a borax bead heated with vanadium compounds depends on the characteristics of the flame, an oxidizing flame rendering the bead yellow, a reducing flame light green.

Hydrogen peroxide added to a cold acid solution of vanadium compounds produces a brown color, which changes to blue on heating. A sensitive and selective method for determination of vanadium is based on the formation of yellow soluble phosphotungstovanadic acid by the addition of phosphoric acid and sodium tungstate to an acid solution of vanadium compounds (13).

The quantitative determination of vanadium depends largely on the associated substances, their nature and their quantity. Gravimetric methods lead to the weighing of mercurous metavanadate, $Hg_2(VO_3)_2$, or of vanadium pentoxide obtained by igniting ammonium metavanadate, NH_4VO_3. Volumetric methods are based on the reduction and reoxidation of vanadium from and to definite levels of valence. Reduction may be effected by hydrogen sulfide, sodium thiosulfate, sulfur dioxide, hydrogen, or organic compounds. Oxidizing agents used are permanganates, iodine, nitric acid, and others.

Vanadium Carbides.

Vanadium carbide, V_4C_3, is of great importance in ferrous metallurgy (see *Vanadium and vanadium alloys*). Several other carbides are known. **Vanadium monocarbide,** VC, is a very hard crystalline substance, 9–10(Mohs), with a high melting point, 2810°C., density 5.36, lattice dimension (NaCl type) $a = 4.30$. It can be produced synthetically in the electric furnace.

Vanadium Cyanides.

Vanadium forms a number of complex cyanides and thiocyanates, such as $K_4V(CN)_6.3H_2O$, $K_3V(CN)_6$ (isomorphous with potassium ferricyanide), and $2KSCN.VO(SCN)_2.5H_2O$.

Vanadium Halides.

Vanadium forms many halides and oxyhalides (see Table II). In general, the halides are hygroscopic and tend to hydrolyze in water. Their stability increases with increasing valence number of the vanadium.

TABLE II. Halides and Oxyhalides of Vanadium.

Classical valency	Fluorine	Chlorine	Bromine	Iodine
2		VCl_2		VI_2
3	VF_3	VCl_3	VBr_3	
	$VF_3.3H_2O$	$VCl_3.6H_2O$	$VBr_3.6H_2O$	$VI_3.6H_2O$
		VOCl	VOBr	
4	VF_4	VCl_4		VI_4
	VOF_2	$VOCl_2$	$VOBr_2$	
5	VF_5			
	VOF_3	$VOCl_3$	$VOBr_3$	
Doubtful		V_2O_2Cl		
		$V_2O_3Cl_2.4H_2O$		
		$VO_2Cl_2.8H_2O$		

Vanadium dichloride (hypovanadous chloride), VCl_2, formula weight 121.86, highly deliquescent green crystals, is made by reducing the tetrachloride with hydrogen, or by heating the trichloride in nitrogen. It is a very strong reducing agent, and it has been suggested as an arsenic remover in the manufacture of hydrochloric acid.

Vanadium trichloride (vanadous chloride), VCl_3, formula weight 157.23 peach-colored plates, can be obtained by the decomposition of the tetrachloride, or by heating vanadium trisulfide, V_2S_3, in chlorine. It is nonvolatile and extremely hygroscopic. The anhydrous chloride can be reduced on heating with hydrogen first to the dichloride and then to an impure metal. The hexahydrate, $VCl_3.6H_2O$, forms green crystals. A trihydrate is also known.

Vanadium tetrachloride (hypovanadic chloride), VCl_4, formula weight 192.78, is a dark red-brown liquid, sp.gr. 1.816, b.p. 148.5°C. It can be readily prepared by passing chlorine over pulverized vanadium metal heated to 180°C., or by passing vanadium oxytrichloride vapor with chlorine over red-hot charcoal, or by heating vanadium carbide in chlorine. It fumes in air and decomposes in water, forming **vanadium oxydichloride,** $VOCl_2$. It slowly decomposes to vanadium trichloride at ordinary temperatures.

Vanadium oxydichloride is marketed in small quantities for the dyeing industry, as a thick liquid known as "divanadyl tetrachloride, sirupy, $V_2O_2Cl_4.5H_2O$." The liquid is also sold absorbed in solid ammonium chloride.

Vanadium oxytrichloride, $VOCl_3$, formula weight 173.32, is a highly mobile, bright yellow liquid, sp.gr. 1.829, b.p. 126.7°C. It is easily prepared by the action of chlorine on a mixture of vanadium pentoxide and carbon at a red heat:

$$V_2O_5 + 3\,C + 3\,Cl_2 \longrightarrow 2\,VOCl_3 + 3\,CO$$

Vanadium oxytrichloride hydrolyzes with water, forming vanadic acid and hydrochloric acid. It is an excellent solvent for organic substances, and also dissolves sulfur. On reduction, lower vanadium oxychlorides are formed, such as $VOCl_2$, VOCl, and ultimately V_2O_2Cl.

Vanadium bromides are less well known. The tribromide, VBr_3, can be prepared by heating powdered vanadium metal and bromine. Several oxybromides, analogous to the oxychlorides, are known to exist.

Vanadium iodides. Vanadium triiodide has been prepared as its hexahydrate, but it is very unstable. A diiodide and a tetraiodide are believed also to exist.

Vanadium fluorides. The fluorides are on the whole similar to the chlorides, but fluorine is the only halogen with which vanadium forms a pentahalide, VF_5, which sublimes when the tetrafluoride is heated in a current of nitrogen.

Vanadium Nitrates.

No vanadium nitrates have been obtained in the solid state, but vanadyl nitrate $VO(NO_3)_2$, probably can exist in solutions up to 10% by weight.

Vanadium Nitrides.

Vanadium mononitride, VN, results when the metal is heated in nitrogen or when ammonia and vanadium compounds react at elevated temperatures. It is very stable to heat, but gives ammonia and vanadium pentoxide on strong heating in steam.

Vanadium dinitride, VN_2, is a black powder formed by passing ammonia over vanadium oxytrichloride. It is unstable, and reverts to the mononitride on exposure to air or on heating.

Vanadium Oxides and Oxysalts (Vanadates).

OXIDES

Vanadium(I) oxide (vanadium suboxide). A brownish coating on metallic vanadium exposed to the atmosphere has been suspected to be V_2O, but this has not been proved.

Vanadium(II) oxide (vanadium monoxide), VO, formula weight 66.95 (sometimes written V_2O_2), is a gray-brown metallic powder, sp.gr. 5.6. It can be prepared by heating *in vacuo* a mixture of vanadium and vanadium trioxide. It is insoluble in water, but is taken into solution by acids, giving vanadium(II) salts.

Vanadium(III) oxide (vanadium trioxide, divanadium trioxide, vanadium sesquioxide), V_2O_3, formula weight 149.90, is a black solid, sp.gr. 4.87. It is formed by the reduction of the pentoxide with carbon or hydrogen. It is oxidized slowly in air at room temperature to the dioxide, more rapidly if heated. The action of chlorine gives the pentoxide and vanadium oxytrichloride:

$$3\ V_2O_3 + 6\ Cl_2 \longrightarrow 4\ VOCl_3 + V_2O_5$$

It is insoluble in water and does not react readily with acids, so that it is not a convenient source for vanadium(III) salts, which are better prepared by reduction of higher salts.

Vanadium(IV) oxide (vanadium dioxide), VO_2, formula weight 82.95 (sometimes written V_2O_4), is a blue-black solid, sp.gr. 4.34, m.p. 1967°C. It can be prepared by partial reduction of the pentoxide, as by heating it to the melting point with oxalic acid, sugar, carbon, or sulfur, or by oxidation of the trioxide in air. It is slightly hygroscopic, and also oxidizes slowly in air. It is amphoteric, and dissolves both in acids and in bases. Acids give vanadyl (VO^{2+}) salts. Solution of the oxide in hot alkalies gives *vanadates (IV)* (hypovanadates, vanadites) of the type $R_2O.xVO_2$.

Vanadium(V) oxide (vanadium pentoxide, divanadium pentoxide), V_2O_5, formula weight 181.90, is by far the best known oxide of vanadium, and is an article of commerce. The impure pentoxide is a brownish red to black powder, sp.gr. 3.36; the pure oxide is yellowish red. Vanadium pentoxide is formed when other vanadium

oxides are heated in air. It is also formed as a precipitate when nitric or sulfuric acid is added to solutions of vanadates, avoiding an excess of acid. It is produced technologically by heating ammonium metavanadate, NH_4VO_3. The heating must be carried out in successive stages, according to a careful time schedule, in order to avoid formation of vanadium(IV) oxide. The commercial product may contain up to 0.2% vanadium(IV) oxide. It is also formed when many vanadium compounds, such as the lower chlorides or oxychlorides, are heated in air.

Vanadium pentoxide melts without dissociating at 660°C., and recrystallizes from the fused state in the form of long red needles. Above the melting point its reactivity is extremely high, and it takes into solution many acidic, basic, and metallic materials. It dissociates into vanadium dioxide and oxygen at temperatures only slightly above the melting point. The dissociation is reversible, and the equilibrium partial pressure of oxygen is reproducible provided the condensed phase remains unchanged, but a great change in oxygen pressure accompanies small changes in composition. This behavior is probably closely associated with the catalytic behavior of vanadium pentoxide (10).

Colloidal solutions of vanadium pentoxide can be formed, as by slowly pouring molten vanadium pentoxide into water. In these sols the vanadium pentoxide is present as rod-like particles, and the sols show stream birefringence.

Vanadium pentoxide is slightly soluble in water, 0.8 g. per 100 ml. of water at 20°C. The solution is acidic. The pentoxide can be taken up in considerably larger quantities by alkaline solutions, which form vanadates, and also by strong acid solutions, which form vanadium(V) salts probably as salts of VO^{3+}. Both in stability and in acid-forming ability, vanadium pentoxide stands between the highest oxides of the two neighboring elements. Thus it is more acid than titanium dioxide, and more stable than chromium trioxide.

VANADATES

It has become customary to speak of orthovanadates, M_3VO_4, pyrovanadates, $M_4V_2O_7$, and metavanadates, MVO_3, but this nomenclature does not reflect the full complexity of the existing compounds. In aqueous solutions vanadates have a strong tendency to form condensed ions; for example, a well-defined anion is hexavanadate, $V_6O_{17}^{4-}$. These condensed ions are not, as in the phosphates, definite polymers held together by predominantly covalent bonds, but are aggregation polymers, held together by bonds showing a considerable amount of ionic character. Their constitution depends on such variables as concentration, temperature, and pH, and their degree of polymerization can be modified by changing these factors.

Acids corresponding in composition to metavanadic acid, HVO_3, and pyrovanadic acid, $H_2V_2O_7$, can be obtained as precipitates.

Ammonium metavanadate, NH_4VO_3, is a well-characterized salt, sp.gr. 2.326. Solubility in 100 g. water, 3 g. at 21°C., 10 g. at 100°C.

Mercurous metavanadate, $Hg_2(VO_3)_2$, sparingly soluble in water, is frequently employed in the quantitative analysis of vanadium.

The **alkali metal vanadates** are white solids, giving colorless solutions. The metavanadates are most frequently obtained by crystallization from solution in the presence of a large excess of alkali. Orthovanadates are the most stable at elevated temperatures, and are formed when vanadium pentoxide is fused with alkalies.

Vanadovanadates are produced when certain alkali carbonates, borates, phos-

phates, etc., are fused with vanadium pentoxide in air. Oxygen is evolved with decrepitation, and some of the vanadium is reduced to the +4 state. These compounds are also produced by the fusion of alkali vanadates.

Double vanadates. Vanadic acid has a strong tendency to form well-crystallized double salts with two or more bases. Many of the naturally occurring minerals correspond in their compositions to double vanadates.

Heteropoly acids containing vanadium are extremely complex and numerous. Again, they must be considered phenomena of hydrolysis and aggregation conditioned by the weak character of the acids and bases of the metal. Jander's work (5) shed some light on the constitution of these compounds, in which the anion apparently polymerizes progressively as the hydrogen-ion concentration increases. Definite polymeric forms appear at certain points as a function of the pH. An example is $7(NH_4)_2O.P_2O_5.12V_2O_5.26H_2O$. At the highest hydrogen-ion concentrations, molecules approach the dimensions of colloidal particles, and, if left standing in this condition, crystals frequently precipitate. See *Heteropoly and isopoly acids.*

Peroxyvanadates, MVO_4. Numerous peroxyvanadates are known. The sodium salt can be prepared by treating a solution of sodium carbonate and ammonium metavanadate with hydrogen peroxide. Peroxyvanadic acid has not been definitely isolated, but it is probably present in a solution prepared by adding vanadium pentoxide to a solution of hydrogen peroxide containing sulfuric acid at low temperatures. On standing or warming, vanadium pentoxide separates out with evolution of oxygen. See *Peroxides, inorganic.*

Vanadium Silicides.

Vanadium silicides, V_2Si and VSi, are formed from vanadium and silicon in the electric furnace.

Vanadium Sulfates.

Vanadium(II) sulfate, $VSO_4.7H_2O$, formula weight 177.12, can be made by cathodic reduction of vanadium pentoxide dissolved in sulfuric acid in the presence of sulfur dioxide. It is readily soluble in water, and strongly reducing. Its double salt with ammonium sulfate, $VSO_4.(NH_4)_2SO_4.6H_2O$, isomorphous with ferrous ammonium sulfate, can be obtained by cathodic reduction of ammonium metavanadate.

Vanadium(III) sulfate, $V_2(SO_4)_3$, formula weight 389.98, a fine crystalline powder, can be obtained by a less drastic reduction of vanadium pentoxide in sulfuric acid. Its solution, probably as $(VO)_2SO_4$, can be obtained by reduction of vanadium pentoxide in sulfuric acid with metallic zinc. It is a powerful reducing agent which bleaches indigo and vegetable dyes. A number of *vanadium alums,* $MV(SO_4)_2.12H_2O$, are known, isomorphous with the aluminum, ferric, and chromium alums.

Vanadium(IV) sulfate. A vanadium(IV) oxysulfate, vanadyl sulfate, $VOSO_4$, can be obtained as a blue solution by reducing vanadium pentoxide in sulfuric acid with sulfur dioxide or oxalic acid. The blue color of this solution is frequently observed in the concentration of ores containing vanadium in the +4 state.

Vanadium(V) sulfate is presumably present, perhaps as $(VO)_2(SO_4)_3$, in the solution of vanadium pentoxide in sulfuric acid, but has not been isolated in the solid state.

Vanadium Sulfides.

There are a number of sulfides, of which the most stable is V_2S_3, a greenish-black solid, sp.gr. 4.7, insoluble in water. It can be prepared by heating any simple vanadium compound in a stream of hydrogen sulfide.

USES

The uses of vanadium compounds are wide in range, since the compounds range widely in characteristics. With a few exceptions, these uses do not require large amounts of vanadium, but some are very important and the number of applications may well expand.

In *catalysis*, vanadium compounds have been found effective for catalyzing both organic oxidation and reduction, but they are in actual use only to assist in oxidizing reactions (14). The oxides of vanadium have found many applications as catalysts, especially in vapor-phase reactions. In the manufacture of sulfuric acid by the contact process, catalysts based on vanadium pentoxide are widely used. See Vol. **10**, p. 487. The conversion of ammonia to nitric acid has also been catalyzed by vanadium pentoxide but is not now practiced industrially.

Another important industrial application of vanadium pentoxide as an oxidizing catalyst is in the conversion of naphthalene to phthalic anhydride. Vanadium pentoxide has also shown its effectiveness in many other organic oxidation reactions where it has been reported in limited industrial use. Among these are anthracene to anthraquinone, toluene to benzaldehyde and benzoic acid, phenanthrene to phenanthraquinone, alcohol to acetaldehyde and acetic acid, diphenylamine to carbazole, benzene to diphenyl and maleic acid, sugar to oxalic acid. In these exothermic partial oxidation reactions, the temperature must be kept uniform throughout the catalyst, both during heating and in operation, and the apparatus is specially designed to this effect. The temperature and time of contact critically affect the yield.

In solution, vanadium pentoxide can catalyze certain oxidation reactions, such as the oxidation by chlorates of primary alcohols to esters and of furfural and pyromucic acid to fumaric acid.

The part played by vanadium compounds in biology is believed to be based on their catalytic function. The stimulating effect of vanadium to plant growth has been observed, and the addition of V as a trace element to fertilizers has been considered. Vanadium occurs in the blood of holothurians and ascidians, among other sea life. In this blood, which contains 3% sulfuric acid, vanadium trioxide is linked in a protein-like chromogen; oxygen transfer is catalyzed, rather than carried as in hemoglobin.

In *medicine* vanadium compounds have been used in minute amounts to achieve diverse therapeutic effects. The element must, however, be present as a stable neutral compound with a minimum of toxicity. It has thus been used: (*1*) as an antiseptic and inhibitor of germ growth, for example, vanadium oxytrichloride in a strong solution of sodium chlorate to treat ulcers, abscesses, open sores, and infected wounds; (*2*) as a chemotherapeutic agent, for example, in gastric catarrhs, vanadium compounds are said to destroy fermentation microbes without impeding digestive enzymes; vanadium compounds also inhibit the growth of a number of organisms which are now fought with antibiotics, for example, spirochetes, pneumococci; (*3*) as a catalyst or oxygen promoter, vanadium compounds counteract the deficiency of hemo-

globin, for example, in anemias, and assist the defensive mechanism in acute infections, such as pneumonia and influenza; in some diseases vanadium compounds boost appetite and improve nutrition and general resistance. Spasmodic research along these lines still continues.

In *dye manufacture and dyeing* vanadium compounds are widely used in the production of aniline black (see Vol. 9, p. 674). Here, vanadium salts are added as catalysts to a mixture of aniline hydrochloride and potassium or sodium chlorate, in a ratio from 1:50,000 to 1:200,000 of catalyst to aniline salt. A very rich black is produced and the overall cost is low.

Vanadium compounds are also used as mordants for the dyeing and printing of cotton, and particularly for fixing aniline black on silk. Ammonium metavanadate has been used as a catalyst in the dyeing of leather and fur black.

Inks from vanadium salts were first made by Berzelius. The addition of a few drops of ammonium vanadate solution to a large quantity of gallnut extract produces a deep black, free-flowing and permanent ink, which slowly changes color to a gray-green. The addition of the vanadium salt to a solution of aniline and sodium chlorate produces marking inks (Jetoline). Ammonium vanadate, pyrogallic acid, and powdered gum arabic produce an indelible ink. Some of the modern quick-drying inks depend for their performance on the addition of ammonium metavanadate.

In *glass making*, vanadium pentoxide is used to eliminate wave lengths below 3589 A. The addition of a mere 0.02% V largely removes the harmful actinic rays which injure the eye and fade fabrics. This type of glass has been used considerably in store windows. In larger amounts vanadium pentoxide produces a greenish-yellow color in glass, the tone varying appreciably with the glass composition.

In *analytical chemistry* ammonium metavanadate is used in oxidation-reduction reactions for volumetric analysis (*vanadometry*) in the direct determination of Fe, Mo, W, U, V, Sn, Cu, and Ti, and in the indirect determination of such elements as Mo, W, U, Cr, P, Pb, Ag, Hg, or Ca. Among organic compounds it may be used to determine citric, maleic, lactic, or tartaric acid in the presence of alcohol or oxalic acid; and for the estimation of many aldehydes, ketones, and carbohydrates which are capable of forming insoluble osazones or phenylhydrazones.

Vanadates give color changes with resorcinol, quinine, strychnine, phenol, aniline, etc., and can be used to analyze for them. Ammonium metavanadate gives a sensitive test for cocaine and other alkaloids containing the benzoyl group, C_6H_5CO.

Vanadium(II) sulfate, VSO_4, may be used in analytical procedure as a reducing agent to determine iron, chromium, copper, and cerium, but, since it is easily oxidized in air, the ammonium double salt, $VSO_4.(NH_4)_2SO_4.6H_2O$, is more satisfactory. The solution may be standardized by ferric ammonium sulfate with potassium thiocyanate as an indicator. It reduces nitrates to nitrites, chlorates to chlorides, peroxysulfates to sulfates, nitro compounds to amines, aldehydes and ketones to alcohols, and dyes to leuco bases.

Other Suggested Uses. Photography might have been expected to have many uses for vanadium with its catalyzing properties, and strong color changes. At an early date Roscoe pointed out that vanadium pentoxide dissolved in strong boiling sulfuric acid produces a dark red color, which, upon dilution with 50 volumes of water and digestion with metallic zinc, changes through blues and greens until it turns to a permanent lavender or violet.

The success of the many attempts to adapt this and other chemical properties

of vanadium to photography has not been marked. However, a "perpetual" developer along these lines has been recommended and some vanadium salts have been used for tinting prints.

Metallic soaps of vanadium have performed well as driers. Compared with the equivalent amounts of manganese and lead driers, vanadium compounds are respectively about two and five times faster in their action on oils, but are somewhat inferior to cobalt driers. Both vanadium and cobalt driers have in common a great uniformity of action throughout the film, without tending to cause surface skins. Both vanadium and lead driers produce very smooth skins without brittleness. Apparently, vanadium driers combine rapid drying with toughness in a smooth-surface film. However, they are too expensive to have come into general use.

The addition of a small amount of vanadium pentoxide to sulfur sprays has been suggested, for the catalytic effect on the oxidation of the sulfur should promote the fungicidal action.

Bibliography

(1) Alexander, J., *J. Soc. Chem. Ind.*, **48**, 871 ff., 895 ff. (1929).
(2) Emeléus, H. J., and Anderson, J. S., *Modern Aspects of Inorganic Chemistry*, Van Nostrand, N.Y., 1952.
(3) Flood, H., and Kleepa, O. J., *J. Am. Chem. Soc.*, **69**, 998–1004 (1947).
(4) Hopkins, B. S., *Chapters in the Chemistry of the Less Familiar Elements*, Stipes Pub. Co., Champaign, Ill., 1939.
(5) Jander, G., *Z. physik. Chem.*, **A187**, 149–69 (1940).
(6) Jander, G., *et al.*, *Z. anorg. u. allgem. Chem.*, **217**, 65–79 (1934).
(7) Latimer, W. W., and Hildebrand, J. H., *Reference Book of Inorganic Chemistry*, 3rd ed., Macmillan, N.Y., 1951.
(8) Mathewson, C. H., *et al.*, *Trans. Am. Soc. Steel Treating*, **20**, 357–84 (1932).
(9) Mellor, Vol. IX, pp. 714–836, 1931.
(10) Milan, E. F., *J. Phys. Chem.*, **33**, 498–508 (1929).
(11) Rankama, K., and Sahama, T. G., *Geochemistry*, Univ. Chicago Press, Chicago, 1949, pp. 594–602.
(12) Saklatwalla, B. D., *J. Ind. Eng. Chem.*, **14**, 968 (1922).
(13) Sandell, E. B., *Colorimetric Determination of Traces of Metals*, Interscience, N.Y.-London, 1950, p. 607.
(14) *Vancoram Rev.*, **1**, 42–44, 116–123, **2**, 55–58 (1930–1932).

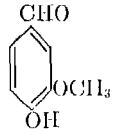
H. E. DUNN AND C. M. COSMAN

VANADIUM STEELS. See *Steel*, Vol. **12**, p. 819; *Vanadium and vanadium alloys.*

VANILLIC ACID, $CH_3O(OH)C_6H_3COOH$. See *Vanillin.*

VANILLIN

Vanillin (vanillaldehyde, 4-hydroxy-3-methoxybenzaldehyde, protocatechualdehyde 3-methyl ether) (I), formula weight 152.14, crystallizes as white or very slightly yellow monoclinic prismatic needles (2,30) and has a pleasant aromatic (vanilla) odor. It is present in small quantities in many plant products, particularly the vanilla pod. It is found in potato parings, in Siam benzoin, in the sugar beet, and in balsams and other natural oils and resins. It is also derived from lignin (*q.v.*), which can be formed in appreciable amounts from the waste sulfite liquors discarded during the manufacture of cellulose pulp by the sulfite process. These liquors are the main source of vanillin at present. Vanillin is the outstanding synthetic flavor in terms of quantities used, partially because of its use in enhancing other flavors. See *Flavors and spices*; *Perfumes (synthetic and isolates)*; *Phenolic aldehydes.*



(I)

Physical and Chemical Properties

Constants. M.p., 80–81°C. (81–83°C., U.S.P.); b.p., 284°C. (decompn.); d_4^{20}, 1.056; heat of soln., 5.2 cal./mole in water at infinite dilution; heat of neutralization, 9.26 cal./mole when a mole of vanillin in 30 liters of water is neutralized with 0.2 *N* NaOH; heat of combustion, 914.7 cal./mole (constant pressure), 914.4 cal./mole (constant vol.). Crystallographic data on vanillin have been reported (18). Data have been compiled on the absorption spectra of vanillin in the following solvents and in the vapor state: ethyl alcohol; ethyl alcohol and sodium ethoxide; ethyl alcohol and sodium hydroxide; hexane (19).

Vanillin is slightly soluble in water (1 part and 5 parts per 100 parts by weight at 14°C. and 75°C., respectively); moderately soluble in glycerol (approx. 4.5% by weight at 25°C.); as well as freely soluble in propylene glycol (approx. 23% by weight at 25°C.), ethyl alcohol (50, 70, and 95%), chloroform, ether, carbon disulfide, glacial acetic acid, pyridine, and solutions of the alkali metal hydroxides.

Reactions. Three different types of reactions are possible with vanillin: those of the aldehyde group, the phenolic hydroxyl, and the aromatic nucleus. The aldehyde group undergoes certain typical aldehyde condensation reactions that allow various substitutions for the aldehyde group. The aldehyde group may also be partially or completely reduced. However, being a *p*-hydroxybenzaldehyde, vanillin does not undergo some very common aromatic aldehyde reactions. These include the Cannizzaro reaction, the benzoin condensation, and oxidation with Fehling solution to the corresponding acid, vanillic acid. If the hydroxyl group in vanillin is protected, oxidation to vanillic acid derivatives readily occurs. As a phenol, vanillin forms esters and ethers, and the nucleus is easily substituted by halogen and nitro groups. In comparison with most other aldehydes, vanillin is notable for its stability.

Condensation. With acetone in the presence of alkali, vanillin forms vanillylideneacetone, which can be reduced to zingerone, m.p. 41°C., the chief flavoring agent of ginger:

$$CH_3O(OH)C_6H_3CHO + CH_3COCH_3 \xrightarrow{-H_2O} CH_3O(OH)C_6H_3CH{=}CHCOCH_3 \xrightarrow{\text{reduction}} CH_3O(OH)C_6H_3CH_2CH_2COCH_3$$

Condensation with hydroxylamine yields vanillin oxime, which is reduced with sodium amalgam and acetic acid to vanillylamine:

$$CH_3O(OH)C_6H_3CHO + NH_2OH \xrightarrow{-H_2O} CH_3O(OH)C_6H_3CH{=}NOH \xrightarrow{\text{reduction}} CH_3O(OH)C_6H_3CH_2NH_2$$

The amides derived from this are pungent materials. Capsaicin, $CH_3O(OH)C_6H_3$-$CH_2NHCO(CH_2)_4CH{=}CHCH(CH_3)_2$, for example, has a potency one thousand times as great as zingerone. With phenylhydrazines, vanillin forms hydrazones. With heptaldehyde in dilute alcoholic potassium hydroxide, vanillin yields α-amyl-3-methoxy-4-hydroxycinnamaldehyde, which has a stronger aroma than jasminal, a fraction of oil of jasmine:

$$CH_3O(OH)C_6H_3CHO + C_6H_{13}CHO \longrightarrow CH_3O(OH)C_6H_3CH{=}C(C_5H_{11})CHO$$

In a Perkin condensation, Tiemann prepared the acetate of ferulic acid, CH_3O-$(CH_3COO)C_6H_3CH{=}CHCOOH$, by prolonged boiling of vanillin with sodium acetate and acetic anhydride. Vanillylidene cyanohydrin, $CH_3O(OH)C_6H_3CH(OH)CN$, can be made by the action of potassium cyanide on a sodium bisulfite solution of vanillin. Vanillylidenenitromethane, $CH_3O(OH)C_6H_3CH{=}CHNO_2$, is prepared from nitromethane by using methylamine hydrochloride and sodium carbonate or ethylamine as the condensing agent.

Reduction. Catalytic hydrogenation using platinum oxide in alcohol, nickel, or palladium-barium in glacial acetic acid as catalyst, or the action of sodium amalgam in water yields *vanillyl alcohol*, m.p. 115°C.:

$$CH_3O(OH)C_6H_3CHO \xrightarrow[\text{catalyst}]{H_2} CH_3O(OH)C_6H_3CH_2OH$$

Creosol, $CH_3OC_6H_3(CH_3)OH$, may also be produced with the palladium-barium catalyst, and hydrovanilloin, $CH_3O(OH)C_6H_3CH(OH)CH(OH)C_6H_3(OH)(OCH_3)$ is an additional product of the sodium amalgam reduction.

Oxidation. For optimum conditions for obtaining high yields of vanillic acid, $CH_3O(OH)C_6H_3COOH$, see p. 609. Dehydrodivanillin (5,5′-bivanillin), OHC-$(CH_3O)(OH)C_6H_2C_6H_2(OH)(CH_3O)CHO$, is obtained in the presence of iron in almost theoretical yields on treatment of vanillin with sodium peroxydisulfate. Optimum yields of methoxyhydroquinone, $CH_3O(OH)C_6H_3OH$, which has antioxidant properties, are obtained by the oxidation of vanillin with alkaline hydrogen peroxide.

Ethers. Methylation (with methyl sulfate and sodium hydroxide) yields veratraldehyde, $(CH_3O)_2C_6H_3CHO$. Ethyl, propyl, isopropyl, and benzyl ethers have also been prepared.

Esters. Acetic anhydride in alkaline solution produces vanillin acetate, while prolonged heating with acetic anhydride, with or without catalysts such as concentrated sulfuric acid, gives the triacetate, $CH_3O(CH_3COO)C_6H_3CH(OOCCH_3)_2$. Benzoyl chloride and alkali give vanillin benzoate (19).

Substitution. Substitution generally occurs in the 5-position when vanillin is halogenated or nitrated. If the hydroxyl group is blocked by esterification or etherification, substitution takes place in the 2- and 6-positions. Vanillin acetate on bromination gives high yields of a 6-bromo derivative, while nitration of the acetate gives

high yields of the 2-nitro derivative, and small amounts of a 6-nitro derivative. Raiford and others (24) have prepared a variety of chlorine-substituted products of vanillin, including monochloro derivatives with substitution in the 2-, 5-, and 6-positions.

Manufacture

FROM GUAIACOL

This is the usual synthetic process. Guaiacol (pyrocatechol monomethyl ether, see Vol. **10,** p. 331), obtained from wood tar by the destructive distillation of hardwood, by distillation of the phenol fraction of coal tar, or through the use as an intermediate of *o*-dichlorobenzene (obtained as a by-product in the manufacture of *p*-dichlorobenzene from the chlorination of benzene), is treated for 2 hr. with 4 parts of 37% formaldehyde and 4 parts of *p*-nitroso-*N*,*N*-dimethylaniline in the presence of 12 parts of methanol poured into water and hydrochloric acid. The methanol is stripped by distillation from the reaction product, which is then extracted with benzene to yield vanillin. On removal of the benzene, the vanillin is filtered and dried (28).

$$CH_3OC_6H_4OH + CH_2O \longrightarrow CH_3O(OH)C_6H_3CH_2OH \xrightarrow{(CH_3)_2NC_6H_4NO}$$
$$CH_3O(OH)C_6H_3CHO + (CH_3)_2NC_6H_4NH_2.HCl$$

FROM NATURAL OILS

From Eugenol. Although first synthesized by Tiemann and Haarmann in 1874 from coniferin, vanillin was later prepared from the cheaper eugenol (4-allylguaiacol, see Vol. **10,** pp. 323, 331–32). Oil of cloves and cinnamon-leaf oil (containing up to 40% eugenol) are treated with alkali, the aqueous solution being separated and acidified. The resulting eugenol is washed and fractionated, then dissolved in dilute sodium hydroxide. This solution is heated under pressure at 160°C. to form the sodium salt of isoeugenol (4-propenylguaiacol) and cooled slightly. One mole of nitrobenzene per mole of original eugenol is then added slowly under pressure to control the oxidation. After venting the gaseous by-products, the reaction mass is acidified with hydrochloric acid to yield vanillin crystals, which are filtered and washed. The yield is 80% of theoretical (8).

$$CH_3O(OH)C_6H_3CH_2CH{=}CH_2 \xrightarrow{NaOH} CH_3O(ONa)C_6H_3CH{=}CHCH_3 \xrightarrow[\text{acid}]{\text{oxidation}}$$
$$CH_3O(OH)C_6H_3CHO$$

From Safrole. Safrole, $O.CH_2.O.C_6H_3CH_2CH{=}CH_2$ (see Vol. **10,** p. 332), which is obtained from camphor oil, gives isosafrole, $O.CH_2.O.C_6H_3CH{=}CHCH_3$, on treatment with alkali. This can be converted to protocatechualdehyde, $(HO)_2C_6H_3CHO$, which yields vanillin on methylation.

FROM WASTE SULFITE LIQUOR

As early as 1898, Pollacsek oxidized waste sulfite liquor (see *Pulp*) with air and ferric chloride and obtained small amounts of vanillin. In 1904, Grafe obtained vanillin in low yields by heating waste sulfite liquor and lime at 180°C. Yields of 5–10% were reported in 1928 by Kürschner (14) on heating waste sulfite liquor with alkali metal hydroxides under various conditions. Acidification of the alkaline reaction

mixture liberated the vanillin, which was extracted with ether or another immiscible solvent. Kürschner (15), Honig and Ruziczka (12), and Shoruigin and Smolyaninova (27) reported on further modifications of this process. However, the need for concentration of large volumes of dilute liquor, the chemical consumption of the carbohydrate fraction of the liquor, and difficulties in the extraction of the vanillin prevented any commercial exploitation of these processes.

Marathon-Howard Processes. These difficulties were overcome by the Marathon-Howard processes (32–34). Dilute waste sulfite liquor is fractionally precipitated with calcium hydroxide, yielding a basic calcium lignosulfonate, free from nonlignin or carbohydrate materials, which is filtered continuously under vacuum. The lignosulfonate is digested under pressure with a concentrated sodium hydroxide solution, 2–3% of the lignin being converted to vanillin. Vanillin, as its sodium salt, is extracted directly from the solution with 1-butanol. The extract is distilled to recover the alcohol. Azeotropic distillation with water removes the last traces of the solvent. The residual water solution of sodium salts is acidified with sulfur dioxide, which precipitates undesirable phenolic materials but leaves the vanillin in solution as a sodium bisulfite addition product. The solution is filtered, further acidified with sulfuric acid, and the sulfur dioxide expelled. The crude vanillin which separates is filtered, then purified by high-vacuum distillation and aqueous recrystallization. This process has been in successful use since 1937 at the Salvo Chemical Corporation plant at Rothschild, Wis.

Howard Smith Process. Tomlinson and Hibbert (29) showed in a systematic study in 1936 that maximum vanillin yields of 6% based on the lignin content of the liquor were obtainable by alkaline hydrolysis of the waste liquor. These workers developed a process entirely different from that of Marathon-Howard, and placed it in operation at the Howard Smith Chemicals, Ltd., sulfite mill in Cornwall, Ontario, at about the same time as the Salvo operation (35). In Cornwall, the waste sulfite liquor is first concentrated and then treated with sodium hydroxide at an elevated temperature and pressure. The solution is then acidified with stack-gas carbon dioxide, and countercurrently extracted with benzene. The caustic in the vanillin-free aqueous liquor is regenerated through incineration and causticization, with some steam recovery. The benzene solution is concentrated by evaporation and the vanillin extracted with sodium bisulfite. Subsequent purification steps are similar to those in the Salvo operation.

The possibility of increasing the vanillin yield in the alkaline cooking of waste sulfite liquor by adding mild oxidizing agents has been explored by various workers. Freudenberg and Lautsch and others showed in 1940–1943 that, with the correct pressure, temperature, concentration, duration, and alkalinity, yields of vanillin up to 20% could be obtained by using air, oxygen, or nitrobenzene as the oxidizing agent (10). It has since been shown (21) that, in addition to nitrobenzene, other low-potential oxidizing agents give high yields of vanillin from waste sulfite liquor and other lignin materials. No commercial developments have as yet been made of these modifications, chiefly because of the large quantities of by-products formed by the oxidation reactions.

Ontario Paper Process. A new process for vanillin production from waste sulfite liquor has recently been developed (45) and is currently used in production at the Ontario Paper Company in Thorold, Ontario. Despite discouraging results by earlier workers, this group devised a process whereby lime instead of sodium hydroxide may

be used for alkaline oxidation of the lignosulfonate. Lime is added to the lignin-containing material, which is presumably a sugar-free waste sulfite liquor. The liquid and sludge that result are agitated, and air is bubbled through the mixture. Excess of lime must be used, as the lignosulfonic acid oxidation products are acidic, and the pH must be maintained above 12. Other critical factors are proper agitation and gas flow, concentration, reaction temperature, and pressure. Following oxidation, the calcium salt of vanillin is present in both the liquid phase and the sludge; at optimum conditions the bulk of the vanillin salt is present in the liquid phase. The liquid is separated by settling or filtration, then acidified with carbon dioxide or other agent to yield vanillin. The process has been adapted to continuous processing and the resulting increase in yields is greater than that predicted by theory (4).

It has been suggested that vanillin may be isolated from dilute aqueous solutions by means of ion-exchange resins rather than by treatment with organic solvents (40).

Economic Aspects

Although the cost of vanillin made from eugenol and similar starting materials has always been high ($6.75/lb. in 25-lb. containers, early 1955), the availability of large amounts of vanillin from waste sulfite liquor has reduced the price considerably. The price of vanillin from waste sulfite liquor (as well as that of vanillin from guaiacol) has remained at $3.00/lb. in 25-lb. containers since about 1945. It is expected that expanding U.S. and Canadian capacity will reduce the price still further.

Synthetic vanillin must compete, to some extent, with natural vanilla extracted from the vanilla pod (see Vol. **6**, p. 589). Although the flavor of the natural product is largely due to its 2–3% content of vanillin, resins and other ingredients of the pod alter the flavor to some extent. The synthetic product will always be of consistent flavor, whereas the natural product will vary to some degree from batch to batch. Marketing of vanillin for flavor uses is to some extent complicated by these differences in extracts from natural sources and the preference of users for vanillin from particular raw materials and blended in specific ways.

Production figures for the synthetic product through 1951 as reported by the U.S. Tariff Commission are shown in Table I. More recent production figures have not been released. However, it is clear that with the new Monsanto ($1.5 million) operation on the West Coast and the similar ($1.3 million) Ontario Paper Co., Ltd., operation at Thorold, Ont., North American production is now of the order of a million and a half pounds annually. It is expected that the new production will find multiple uses in fields other than the already well-supplied flavor field. It is expected too that the by-products of vanillin production will find new and extended uses as the price of vanillin drops (see p. 609). Figures on imports of vanillin are not available, but they are believed to be negligible.

TABLE I. U.S. Production and Sales of Vanillin 1946–1951.

Year	Production, lb.	Sales, lb.	Value, $	Unit value, $/lb.
1946	566,400	574,100	1,400,900	2.44
1947	963,900	891,400	2,735,000	3.07
1948	932,400	793,200	2,190,700	2.76
1949	856,900	852,800	2,245,600	2.64
1950	964,200	980,300	2,845,700	2.90
1951	999,000	906,000	2,654,000	2.93

Grades and Specifications

Vanillin is available in the U.S.P. grade in cartons, bottles, cans, and drums. It is also available in reagent and technical grades. The U.S.P. grade should not lose more than 1% of its weight on drying for 4 hours over sulfuric acid; and it should not leave more than 0.05% residue on ignition. Vanillin should be stored in tight, light-resistant containers. It slowly oxidizes on exposure to moist air.

Analysis

Identification. Vanillin can be identified by the following tests (31). When a solution of ferric chloride is added to a cold saturated vanillin solution, a blue color is produced which changes to brown when the solution is heated to 80°C. for a few minutes. On cooling, a white precipitate deposits. Vanillin can be extracted from an ether solution by means of sodium bisulfite solution, then precipitated by acids. It can also be identified by the white precipitate which results when lead acetate solution is added to a cold solution of vanillin. The precipitate is soluble in acetic acid, but only sparingly soluble in hot water.

Determination. A sensitive colorimetric method that detects 0.2 mg. of vanillin with accuracy is that of Folin and Denis (9), in which phosphotungstic and phosphomolybdic acids are used. However, 10% sodium carbonate is advised in place of the 20% solution originally recommended. The modification is the recommended A.O.A.C. colorimetric method for vanillin (1). The photometric method of Daniels and his co-workers (5), using ammonium *o*-iodoxybenzoate, is accurate within 2–3%.

The gravimetric method of Iddles and his co-workers (13), in which vanillin is precipitated as the 2,4-dinitrophenylhydrazone, suffers from the disadvantage that the reagent will precipitate any water-soluble aldehyde or ketone. A more specific reagent for gravimetric determination is *m*-nitrobenzoic acid hydrazide, although this reagent will precipitate such aldehydes as veratraldehyde and syringaldehyde. The yield of vanillin is about 98.6% of theoretical, and a correction factor may be applied.

A rapid ultraviolet absorption technique, which is applicable to vanillin and coumarin mixtures and gives excellent reproducibility, is that of Englis and Hanahan (7). The method involves dilution, precipitation with lead acetate, extraction with ethyl ether, and dilution of the ether extract to a large volume with water. Total vanillin and coumarin are estimated from the absorption at 2875 A. The proportions of each present are calculated from a simple equation involving values at 2313 A.

A spectrophotometric method for vanillin determination (17) depends on the fact that when solutions of *p*-hydroxy aldehydes and ketones in ethyl alcohol are made alkaline, the long-wave bands of their ultraviolet absorption spectra are displaced to the high ultraviolet (328–370 mμ). The concentration of any one of these compounds can be determined by measuring the density of an alkaline solution in comparison with a nonalkaline solution at the wavelengths of maximum absorption. The method has been applied to the determination of vanillin alone, vanillin and syringaldehyde, and vanillin and coumarin mixtures.

Uses

About 80–85% of present vanillin production is used as a flavoring agent for ice cream, candies, cookies, gelatin desserts, soft drinks, etc. The balance is used mainly for deodorizers (for example, for rubber), perfumes, exports, and industrial uses. It is

also used to some extent to flavor pharmaceutical preparations. It has no appreciable physiological activity in the small amounts usually employed.

In perfumes vanillin finds considerable use as a modifier or a fixative (see *Perfumes (isolates and synthetics)*). It may be used to impart sweetness to practically any type of odor, while its own characteristic flavor remains masked.

The industrial uses of vanillin, which are becoming increasingly significant, include the prevention of foaming in lubricating oils (43); the preparation of syntans for tanning (44); use as a brightener in zinc plating baths (6); as an aid to the oxidation of linseed oil (11); and as a solubilizing agent for riboflavin (41). Vanillin has also been used in the synthesis of papaverine, and in preparing other potentially useful derivatives. These include certain hydrazones of vanillin that have a plant-killing action similar to 2,4-D (26) and the zinc salt of dithiovanillic acid (formed by the reaction of vanillin and ammonium polysulfide in alcoholic hydrochloric acid), which is a vulcanization inhibitor (3). 5-Hydroxymercurivanillin, 5-acetoxymercurivanillin, and 5-chloromercurivanillin have been prepared and found to have disinfectant properties (42). Although the 5-hydroxy compound possesses a toxicity towards microorganisms comparable with sodium pentachlorophenate and ethylmercuric phosphate, its toxicity towards fish is much less. It is therefore of potential interest as a slime-control agent in mills where wastes are discharged into fishing streams.

Derivatives and Related Compounds

Ethyl vanillin (3-ethoxy-4-hydroxybenzaldehyde, bourbonal, vanillal), $C_2H_5O(OH)C_6H_3CHO$, formula weight 166.17, m.p. 77–78°C., occurs as white crystalline needles completely soluble in ethyl alcohol. Ethyl vanillin is a synthetic flavoring and aromatic agent of similar odor and flavor to vanillin, but much more intense. It is sold under such trade names as Ethavan and Vanaldol, and was priced (early 1955) at $6.75/lb. in 25-lb. cans.

Vanillic acid (4-hydroxy-3-methoxybenzoic acid, $CH_3O(OH)C_6H_3COOH$, formula weight 168.14, forms colorless needles from water, m.p., 207°C., and sublimes on heating. It is soluble to the extent of 0.12 gram and 2.5 grams in 100 ml. water at 14 and 100°C., respectively. Vanillic acid is very soluble in ethyl alcohol and ethyl ether.

Controlled potassium hydroxide fusion of vanillin gives very high yields of vanillic acid (23), and vanillin is oxidized almost quantitatively to the acid by silver oxide (20):

$$CH_3O(OH)C_6H_3CHO \xrightarrow{\text{oxidation}} CH_3O(OH)C_6H_3COOH$$

Oxidations of vanillin have also been effected with mercuric and auric oxides (37). A good yield of vanillic acid may also be obtained by treatment of vanillin oxime with acetic anhydride followed by hydrolysis (25). In addition to processes for making vanillic acid from vanillin, several methods of producing vanillic acid in high yield directly from isolated lignosulfonates and waste sulfite liquor have been found (38,39).

Vanillic acid esters are easily prepared in high yield from vanillic acid and the appropriate alcohol. These esters have been used as nontoxic food preservatives, slime-control agents, disinfectants, in pharmaceuticals, and in suncreams.

Ethyl vanillate, $CH_3O(OH)C_6H_3COOC_2H_5$, formula weight 196.20, occurs as colorless needles, m.p., 44°C.; b.p. 293°C.; it is insoluble in water, very soluble in ethyl

alcohol and ether, and soluble in alkalies. Ethyl vanillate is less toxic than sodium benzoate when administered in oil. During World War II, the U.S. Food and Drug Administration agreed to consider the use of ethyl vanillate as a preservative in amounts up to 0.10% where it could be shown that such use would permit the delivery of acceptable food products to the Armed Forces. Ethyl vanillate has been shown to have remarkable preservative properties in such foods as salt fish and fresh fruit (22).

Acetovanillone (4-hydroxy-3-methoxyacetophenone, apocynin), $CH_3COC_6H_3(OH)OCH_3$, formula weight 166.17, crystallizes from water as colorless prisms, m.p. 115°C.; b.p., 295–300°C.; it is very soluble in hot water; 7.7 grams dissolve in 100 grams of ethyl alcohol at 9°C.; soluble in ether and benzene and insoluble in petroleum ether. Acetovanillone may occur as an impurity (up to 3%) in vanillin as prepared from waste sulfite liquor. For many chemical purposes, crude vanillin containing a small amount of acetovanillone as an impurity is available commercially and may be substituted for pure vanillin.

Bibliography

(1) A.O.A.C., 7th ed., 1950, p. 306.
(2) Beilstein, 4th ed., Vol. VIII, p. 247 *et seq.*
(2a) Brenck, H., and Muller, H., *Ber.*, **B75**, 561–65 (1943).
(3) Bruni, G., and Levi, T. G., *Atti. acad. Lincei*, **32**, i, 5–8 (1923); *Chem. Zentr.*, **1923**, III, 1642.
(4) *Chemical Week*, **71**, 33–34 (1952).
(5) Daniels, T. C., Emery, B., and Prather, D., *Ind. Eng. Chem., Anal. Ed.*, **10**, 320–21 (1938).
(6) Eckardt, W., *Oberflachentech.*, **18**, 170–71 (1941); *Chem. Zentr.*, **1942, I**, 1936.
(7) Englis, D. T., and Hanahan, D. J., *Ind. Eng. Chem., Anal. Ed.*, **16**, 505–7 (1944).
(8) Faith, W. L., Keyes, D. B., and Clark, R. L., *Industrial Chemicals*, Wiley, N.Y., 1950, pp. 624–30.
(9) Folin, O., and Denis, W., *J. Ind. Eng. Chem.*, **4**, 670–72 (1912).
(10) Freudenberg, K., Lautsch, W., and Engler, K., *Ber.*, **B73**, 167–71 (1940).
(11) Hadert, H., *Farbe u. Lack*, **56**, 349–51 (1950).
(12) Honig, M., and Ruziczka, W., *Z. angew. Chem.*, **44**, 845 (1931).
(13) Iddles, H. A., Low, A. W., Rosen, B. D., and Hart, R. T., *Ind. Eng. Chem., Anal. Ed.*, **11**, 102–3 (1939).
(14) Kürschner, K., *J. prakt. Chem.*, **118**, 238 (1938).
(15) Kürschner, K., *Tech. Chem. Papier-Zellstoff Fabr.*, **30**, 1 (1933).
(16) Kürschner, K., and Schramek, W., *Tech. Chem. Papier-Zellstoff Fabr.*, **28**, 65 (1931); **29**, 35 (1932).
(17) Lemon, H. W., *Ind. Eng. Chem., Anal. Ed.*, **19**, 846–49 (1947).
(18) McCrone, W. C., *Anal. Chem.*, **22**, 500 (1950).
(19) Ontario Paper Co., Ltd., *Lioxin, A Combined Phenol and Aldehyde*, Thorold, Ont., Can., 1953, 16 pp.
(20) Pearl, I. A., *J. Am. Chem. Soc.*, **68**, 429–32 (1946); **68**, 1100–1 (1946).
(21) Pearl, I. A., *J. Am. Chem. Soc.*, **64**, 1429–31 (1942).
(22) Pearl, I. A., *Food Inds.*, **17**, 1173 (1945); Pearl, I. A., and McCoy, J. F., *ibid.*, **17**, 1458 (1945).
(23) Pearl, I. A., *J. Am. Chem. Soc.*, **68**, 2180–81 (1946).
(24) Raiford, L. C., and Lichty, J. G., *J. Am. Chem. Soc.*, **52**, 4576 (1930).
(25) Raiford, L. C., and Potter, D. J., *J. Am. Chem. Soc.*, **55**, 1682–85 (1933).
(26) Reed, H. S., Dufrenoy, J., Parikh, J. R., and Oneto, J. R., *Compt. rend.*, **230**, 2317–18 (1950).
(27) Shorygin, P. P., and Smolyaninova, E. K., *J. Gen. Chem. (U.S.S.R.)*, **4**, 1428 (1934)
(28) Shreve, R. N., *Chemical Process Industries*, McGraw-Hill, N.Y., 1945, pp. 567–68.
(29) Tomlinson, G. H., and Hibbert, H., *J. Am. Chem. Soc.*, **58**, 345–348 (1936).
(30) Ullman, 2nd ed., 1931, Vol. VIII, pp. 815–20.
(31) U.S.P. XIV, 1950, p. 657.
(32) U.S. Pat. Re. 18,268 (Dec. 1, 1931), G. C. Howard (to Guy C. Howard Co.). Reissue of 1,699,845 (Jan. 22, 1929).

(33) U.S. Pat. 1,856,558 (May 3, 1932), G. C. Howard.
(34) U.S. Pat. 2,057,117 (Oct. 13, 1936), L. T. Sandborn, J. R. Salvesen, and G. C. Howard (to Marathon Paper Mills Co. and Guy C. Howard Co.).
(35) U.S. Pat. 2,069,185 (Jan. 26, 1937), H. Hibbert and G. H. Tomlinson, Jr. (to Howard Smith Chemicals, Ltd.).
(36) U.S. Pat. 2,104,701 (Jan. 4, 1938), L. T. Sandborn (to Marathon Paper Mills Co. and Guy C. Howard Co.).
(37) U.S. Pat. 2,414,119 (Jan. 14, 1947), I. A. Pearl (to Cola G. Parker as trustee).
(38) U.S. Pat. 2,431,419 (Nov. 25, 1947), I. A. Pearl (to Sulphite Products Corp.).
(39) U.S. Pat. 2,433,227 (Dec. 23, 1947), H. F. Lewis and I. A. Pearl (to Sulphite Products Corp.).
(40) U.S. Pat. 2,449,364 (Sept. 14, 1948), A. Blankart (to Hoffmann-La Roche, Inc.).
(41) U.S. Pat. 2,449,640 (Sept. 21, 1948), J. Charney (to Wyeth, Inc.).
(42) U.S. Pat. 2,489,380 (Nov. 29, 1949), H. F. Lewis and I. A. Pearl (to Sulphite Products Corp.).
(43) U.S. Pat. 2,528,465 (Oct. 31, 1950), V. N. Borsoff and J. O. Clayton (to California Research Corp.).
(44) U.S. Pat. 2,564,022 (Aug. 14, 1951), J. Miglarese (to U.S. Leather Co.).
(45) U.S. Pat. 2,576,752; -753 (Nov. 27, 1951), J. H. Fisher and H. B. Marshall (to The Ontario Paper Co., Ltd.).
(46) U.S. Pat. 2,576,754 (Nov. 27, 1951), J. H. Fisher and C. A. Sankey (to The Ontario Paper Co., Ltd.).

DESMOND M. C. REILLY

VANISHING CREAM. See *Cosmetics*, Vol. 4, p. 535.

VANTHOFFITE, $3Na_2SO_4.MgSO_4$. See *Magnesium compounds*, Vol. 8, p. 614.

VAPOR-LIQUID EQUILIBRIA AND VAPOR PRESSURE

In general, this discussion will consider the conditions of equilibrium between a liquid and the vapor in contact with it. Temperature, T, is the first consideration, and the *independent* variable, as almost always. If the liquid is a single component, the other function or *dependent* variable is the vapor pressure, P, a measure of the tendency to escape from the liquid phase into the vapor phase. This increases with temperature. If the liquid has dissolved in it a nonvolatile solute, increasing concentrations of the nonvolatile component will reduce markedly the vapor pressure of the volatile component at the same temperature.

If both components are volatile, a change in x, the composition in the liquid of the more volatile one, will not only affect P (as will also changes in T), but it will also affect the relative amounts of the components volatilized; that is, the composition of the vapor, y. For solutions of two volatile components, the composition of the liquid x and of the vapor y may be expressed as single numbers representing the mole fraction or percentage of the more volatile component. The difference between unity or 100% and the given value of x or of y gives the composition of the less volatile component.

In a ternary solution the composition of the most volatile is indicated first; that of the next most volatile one second; and the concentration of the least volatile one is the sum of these subtracted from unity or 100%. Solutions of four or more components follow the same system.

One important magnitude is the energy that has to be added to a condensed phase (liquid or solid) to account for the increased molecular activity in changing a part or all of it to the dispersed phase (vapor). This is called the *latent heat of vaporization* and

may be expressed per mole or per unit of mass. An equivalent amount is subtracted when the vapor condenses as the *heat of condensation*.

Because of the widespread scientific and engineering importance of vapor pressures of liquids, as well as of vapor compositions in equilibrium with liquid compositions, there have been numerous references to these interesting functions in many other articles, such as *Absorption*; *Adsorption*; *Data*; *Distillation*; *Evaporation*; *Gases and vapors*; *Phase rule*; *Thermodynamics*.

Vapor Pressure of One Component

There is always a tendency for the molecules to escape from a condensed to a dispersed phase; and, for even the least volatile material, there is assumed to be an

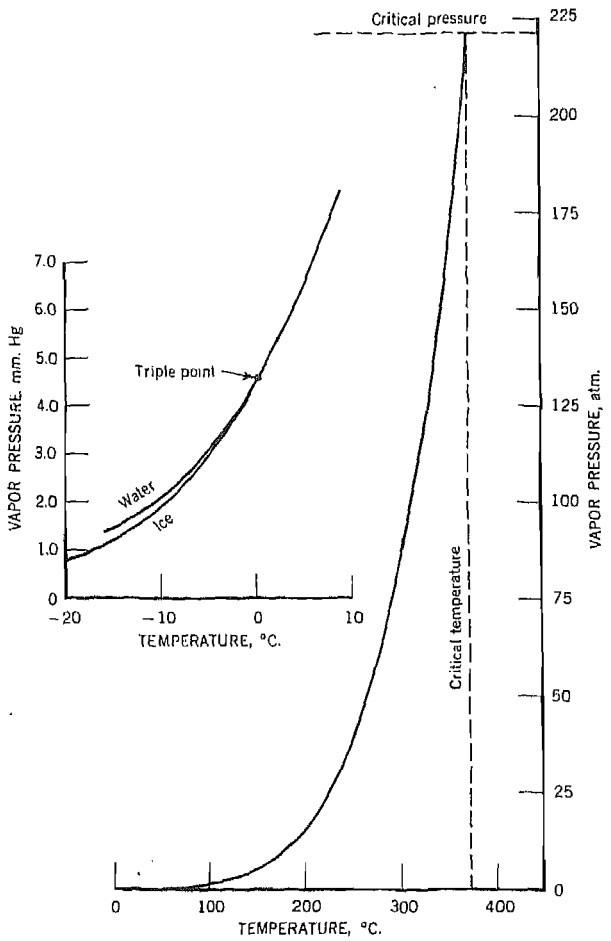


Fig. 1. Typical vapor pressure curve: for water from 0°C. to critical conditions, and for water and ice near the triple point.

equilibrium vapor pressure, although this may be immeasurably small. Many compounds decompose as the temperature rises, and before a measurable vapor pressure exists. With higher temperatures, vapor pressure is higher; with lower temperatures it is lower; this is a very definite relation, which is one of the most precise and repro-

ducible of physical-chemical properties of matter, particularly liquids, since most solids have comparatively low vapor pressures. When passing from a solid to a liquid phase, or through a polymeric or other molecular rearrangement still in a condensed phase, this relation of P with T will change abruptly for each molecular arrangement. The normal vapor pressure curve for water is shown in Figure 1; it would appear much the same for most single components.

Thus, for a solid there will be a definite vapor pressure relation, the mathematical evaluation of which will be discussed later. This relation changes at that temperature where the solid melts under its own vapor pressure (the so-called triple point). The new vapor pressure relation or curve of the liquid increases up to the so-called "critical point." This critical temperature is the highest temperature at which the material may be kept in the liquid phase in equilibrium with its vapor; and the corresponding vapor pressure (critical pressure) is also the highest. The latent heat of vaporization becomes smaller with increasing temperature. At the critical point it becomes zero; there is no difference between the liquid and vapor densities, and no interface of demarcation of the phases at the critical point. Since the term "vapor" presupposes "vaporization" and none such takes place above the critical point, the dispersed phase above the critical temperature is called a "gas."

Langmuir (20) considered the kinetic equilibrium at an interface between a condensed phase (solid or liquid) and a vapor phase; and he expressed the mass rate of evaporation (m, per unit surface) therefrom as:

$$m = (M/2\pi RT_L)^{1/2}P$$

where M is molecular weight, R is the gas constant, T_L is the absolute temperature of the liquid side of the interface, and P is the vapor pressure. The continuous gain of the condensed phase by condensation of vapor molecules would be given by the same expression, with T_V the absolute temperature of the vapor side of the interface. The net rate of evaporation or of condensation is the difference between these kinetic rates.

Othmer (28) showed that the heat, Q, transferred across this interface may be calculated, if the Clausius-Clapeyron equation (defined below) is substituted in this kinetic equation. The expression then is:

$$Q = \left(\frac{R}{2\pi M}\right)^{1/2} \frac{dP}{dT} (T_L^{3/2} - T_V^{3/2})$$

where dP/dT is the slope of the vapor pressure line for this small temperature range.

This interesting heat transfer relation shows a variation with the 3/2 power of high and low temperatures, rather than the first power as in conduction, or the fourth power as in radiation phenomena. In any practical operation, this net rate is exceedingly small compared to the number of molecules passing across the interface from the liquid to the vapor phases, and vice versa. This may be shown by a substitution of values for the heat transferred and other quantities in any actual operation. This will give an extremely low value of the temperature function difference; that is, the difference of temperature between the liquid and the vapor. For all practical purposes it may thus be assumed conversely that the vapor pressure of a liquid is always equal to that at equilibrium, even though evaporation (or condensation) may be taking place at the highest rates encountered in engineering practice. Also, this explains why superheated water (as from a steam trap) vaporizes with explosive speed when discharged

to a lower pressure; since the driving force, the difference of the temperature function, can cause such a tremendous transfer of the heat of vaporization in unit time.

In isolated systems, or those in which there is no heat input to cause vaporization of a volatile component, it is assumed that the rates of vaporization and condensation are equivalent; and the net effect in either direction is zero. Nevertheless, the pressure engendered by the escaping molecules, for example from a volatile liquid in a closed bottle, is such that the vapor pressure of that liquid at that given temperature is always present and is definite and reproducible. (Through careful measurement, it is a test of the purity of the compound.) If the bottle is vented and the vapors escape, continual evaporation takes place to equal the net escaping tendency at the ambient temperature. Heat of vaporization must be supplied, however. In an isolated or insulated system such heat can come only from that of the liquid itself, which is thereby cooled down to a temperature where the escaping tendency is in equilibrium with the ambient vapor pressure; and there is no further evaporation. (This is an application of LeChatelier's principle.)

Mathematical Expression of Vapor Pressure with Temperature. The exact relationship between vapor pressure and temperature is a consequence of the first and second laws of thermodynamics (*q.v.*) (see also *Gases and vapors*) and is expressed in *molar quantities* as:

$$dP/dT = L/(V_G - V_L)T$$

where P is the vapor pressure, T is the absolute temperature, L is the heat of vaporization, V_G is the volume of vapor, and V_L is the volume of liquid.

This equation may be written as the Clausius-Clapeyron equation by assuming that: (*1*) the liquid volume is negligible compared to vapor volume, and (*2*) the vapor may be treated as an ideal gas (that is, $PV_G = RT$, where R is the gas constant):

$$dP/dT = LP/RT^2$$

Many theoretical and empirical methods of correlating and plotting vapor pressure data have been proposed. These depend on the integrated form of the Clausius-Clapeyron equation, in which the heat of vaporization is assumed constant:

$$\log P = B - (A/T)$$

Another form is the Antoine equation:

$$\log P = B - A/(C + T)$$

Tables of these constants, A, B, and C, for many substances have been computed. For short ranges of temperature these equations hold, and yield a line that is almost straight when $\log P$ is plotted against the reciprocal of T. For greater ranges of temperature the lines become more curved, indicating that the assumptions are not applicable. A principal one is that the latent heat is constant and this does not hold since, as temperatures increase, this decreases. Another is the assumption of the ideal gas laws, which are widest in their deviations for vapors near their condensing points.

Numerous empirical equations have been devised as extended modifications of these to express more accurately vapor pressure relations by means of from 3 or 4 to 8 or 10 constants and temperature values raised to various powers.

One empirical correlation of vapor pressures is the Cox chart (10), developed for substances of the same family, such as the series of straight-chain aliphatic hydro-

carbons. On a sheet of unruled paper the pressure scale is laid off logarithmically from a slide rule. A straight line at a suitable angle, assumed as the curve for saturated steam, is laid off from this. For each temperature, the corresponding pressure (from the steam table) is marked on the diagonal axis and projected to the temperature scale. Members of families of homologous hydrocarbons are plotted against this "entirely arbitrary" temperature scale; they yield substantially straight vapor pressure lines which have been said to intersect in a single focal point, although careful work shows that this is not exactly the case. One drawback of this empirical plot is the nuisance of preparing and ruling from a blank sheet the graph paper to be used; and another is that no provision is indicated for interrelating heats of vaporization.

The principle of utilizing a standard reference substance in vapor pressure correlation was first employed, entirely empirically, in the Dühring chart. Here the boiling point of a given substance is plotted against the boiling point of a reference substance taken at the same total pressure. Lines that are almost straight result, providing the range of temperature is not too great. Compare Vol. **1,** p. 408. Here again no provision is made for interrelating latent heats of vaporization. Because the correlation is in terms of temperature as the dependent variable, it is awkward to use for vapor pressure data which are usually tabulated at even values of temperature. The Dühring chart has been modified to increase its range by replacing the temperature with the logarithm of the absolute temperature—this is the so-called Li chart (21). A still more accurate method of plotting that gives a similar effect to the one next discussed is that of Perry and Smith (48) for reciprocal temperatures at the same values of pressure.

A more recent method of correlation (29) eliminates most of the objections given above; thus, it has been shown (see *Data (correlation)*) that a convenient and relatively accurate expression of vapor pressure as a function of temperature may be made utilizing a reference substance, and the equation:

$$\log P = (L/L') \log P' + C$$

In this, C is a constant of integration having the desired units of pressure; and L' and P', respectively, are molar latent heat and vapor pressure of the reference substance which is always taken at the same temperature as that for the substance in question. L/L', the ratio of the molar latent heats, is a very useful term by itself and is identified as m.

This function presupposes the constancy of the *ratio* of the molar latent heats of the two liquids (preferably not too different in their properties). Both are diminishing according to the same law with increasing temperature (as indicated above, since at the critical points they must vanish). It follows that the ratio is much more nearly constant than is either one singly. Furthermore, this reference substance equation, by relating the changing function of two substances, minimizes the absolute deviations of each from ideality of the gas laws, which are other assumptions of the familiar log P versus $1/T$ plot. This is done by comparing the similar deviations of two different vapors at their condensation points.

The values for vapor pressures may readily be calculated for any substance using this equation and the appropriate constants m and C. For some 600 compounds these constants have been tabulated (38) on the basis of water as a reference substance and in units of millimeters of mercury, pounds per square inch, and atmospheres. Table I is a listing for a score of representative compounds. Thus, to determine the vapor

pressure of a compound, such as acetic acid at 160°C., the vapor pressure of water at this temperature is taken from a standard source as 4,670 mm. The values of m = 0.960 and $C_{\text{mm.}} = -0.148$ are taken from Table I. Substituting in the above equations gives:

$$\log P = 0.960\ (3.670) - 0.148 = 3.374$$

from which P = 2,370 mm. This compares favorably with the accepted value of 2,400 mm. from the literature.

Pressures may be expressed in any desired units, but the corresponding values of C must be used. Values of C are given in Table I for pressure units in pounds per square inch absolute, millimeters of mercury, and atmospheres. The value of C_x for any pressure unit is determined from the value of $C_{\text{atm.}}$ from the basic equation:

$$C_x = C_{\text{atm.}} + (1 - m) \log P_x$$

where P_x = number of pressure units per atmosphere. For example, $C_{\text{mm.}} = C_{\text{atm.}} + (1 - m) \log 760 = C_{\text{atm.}} + 2.881\ (1 - m)$.

TABLE I. Values of m and of C for Various Liquids.

	For use in equation or in nomogram, Fig. 3		For use only in equation	
	Latent heat ratio, m	$C_{\text{atm.}}$	$C_{\text{mm.}}$[a]	$C_{\text{p.s.i.a.}}$[b]
n-Pentane	0.633	+0.773	+1.831	+1.201
n-Hexane	0.720	+0.380	+1.187	+0.706
n-Heptane	0.807	+0.015	+0.571	+0.240
n-Octane	0.909	−0.338	−0.076	−0.232
Benzene	0.770	+0.250	+0.913	+0.518
Ethylbenzene	0.940	−0.470	−0.297	−0.400
Toluene	0.853	−0.137	+0.286	+0.034
n-Butylbenzene	1.115	−1.142	−1.474	−1.276
Carbon tetrachloride	0.722	+0.278	+1.079	+0.602
Chloroform	0.718	+0.485	+1.298	+0.814
Chlorobenzene	0.900	−0.410	−0.122	−0.293
3-Chlorotoluene	1.035	−0.837	−0.938	−0.878
1,2-Dichloroethane (ethylene dichloride)	0.770	+0.200	+0.863	+0.568
Methanol	0.885	+0.532	+0.864	+0.666
Ethanol	0.958	+0.340	+0.461	+0.389
n-Butanol	1.090	−0.300	−0.560	−0.405
Acetic acid	0.960	−0.263	−0.148	−0.216
Ethyl acetate	0.785	+0.300	+0.920	+0.551
Aniline	1.170	−1.220	−1.710	−1.418
Carbon disulfide	0.660	+0.650	+1.630	+1.046
Acetone	0.737	+0.555	+1.313	+0.862
Ethyl ether	0.638	+0.800	+1.843	+1.223

[a] $C_{\text{mm.}} = C_{\text{atm.}} + (1 - m) \log 760$.
[b] $C_{\text{p.s.i.a.}} = C_{\text{atm.}} + (1 - m) \log 14.7$.

Log P vs. Log P' Vapor Pressure Plot. The method of making this vapor pressure plot *on standard logarithmic paper* is through the use of a reference substance whose vapor pressures (and latent heats, desirably) are known at the desired temperatures. The X axis is calibrated for the vapor pressure of the reference substance, and it has

corresponding uniformly chosen points of temperature indicated thereon. Vertical lines are erected for the temperature ordinates at these points; and values of vapor pressures from the logarithmic Y axis are plotted directly against these temperatures to give points falling on a straight line. For example, in Figure 2 the data are plotted for acetone against water as a reference substance.

The slope of the line represents the ratio of the molar latent heat of acetone to the molar latent heat of water at any given temperature. Obviously, it is possible with two values of the vapor pressure, such as the boiling point and one other value, to represent the function throughout the entire range. Alternately, a line might be plotted from a single point (for example, the boiling point) and the slope of the line, as obtained from the relative molar latent heat of the liquid in question at any temperature divided by the molar latent heat of water at the same temperature.

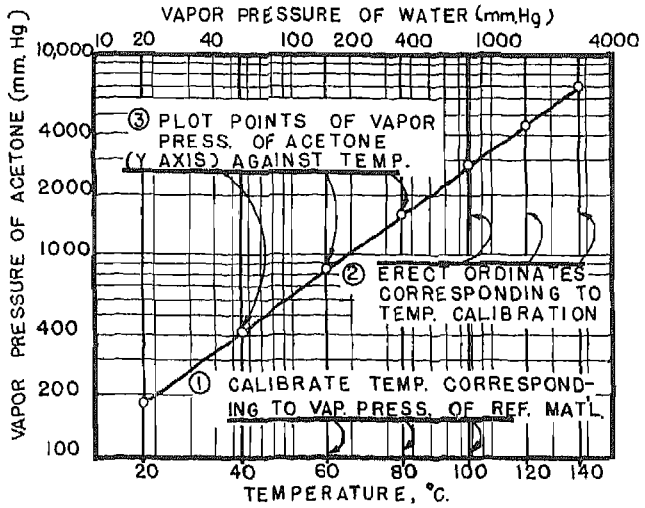

VAPOR PRESSURE OF WATER (mm.Hg.)
10 20 40 100 200 400 1000 4000
VAPOR PRESSURE OF ACETONE (mm. Hg.)
10,000
4000
2000
1000
400
200
100
③ PLOT POINTS OF VAPOR PRESS. OF ACETONE (Y AXIS) AGAINST TEMP.
② ERECT ORDINATES CORRESPONDING TO TEMP. CALIBRATION
① CALIBRATE TEMP. CORRESPONDING TO VAP. PRESS. OF REF. MAT'L.
20 40 60 80 100 120 140
TEMPERATURE, °C.

Fig. 2. Method of making logarithmic plot of vapor pressure of acetone vs. vapor pressure of water at the same temperature. The three steps are shown, starting with a standard sheet of logarithmic paper.

For homologous series, the vapor pressure lines of successive members intersect the line of any one at a spaced relationship that may be determined (29). These intersections are far outside of possible vapor pressures (being above the critical) and not far apart. If data for only one member of the series are lacking, the line may be drawn using only one point (or the slope from the latent heat relationship) and the intersection that may be estimated. If several or more members have conclusive data missing, lines may be drawn from one intersection and single points, within the accuracy requirements of most engineering work.

The plotting method indicated above is adequate for practical uses and equals the precision of most experimental measurements when standard, usual size logarithmic graph paper is used. The equation itself may also be used directly, with results as close to the probable correct value as most experimental measurements. Greater precision may be obtained, when the data warrant, through the use of larger-size graph paper, since very accurate vapor pressure data of suitable reference substances are available. (When inconvenient ranges are involved, ordinary graph paper may

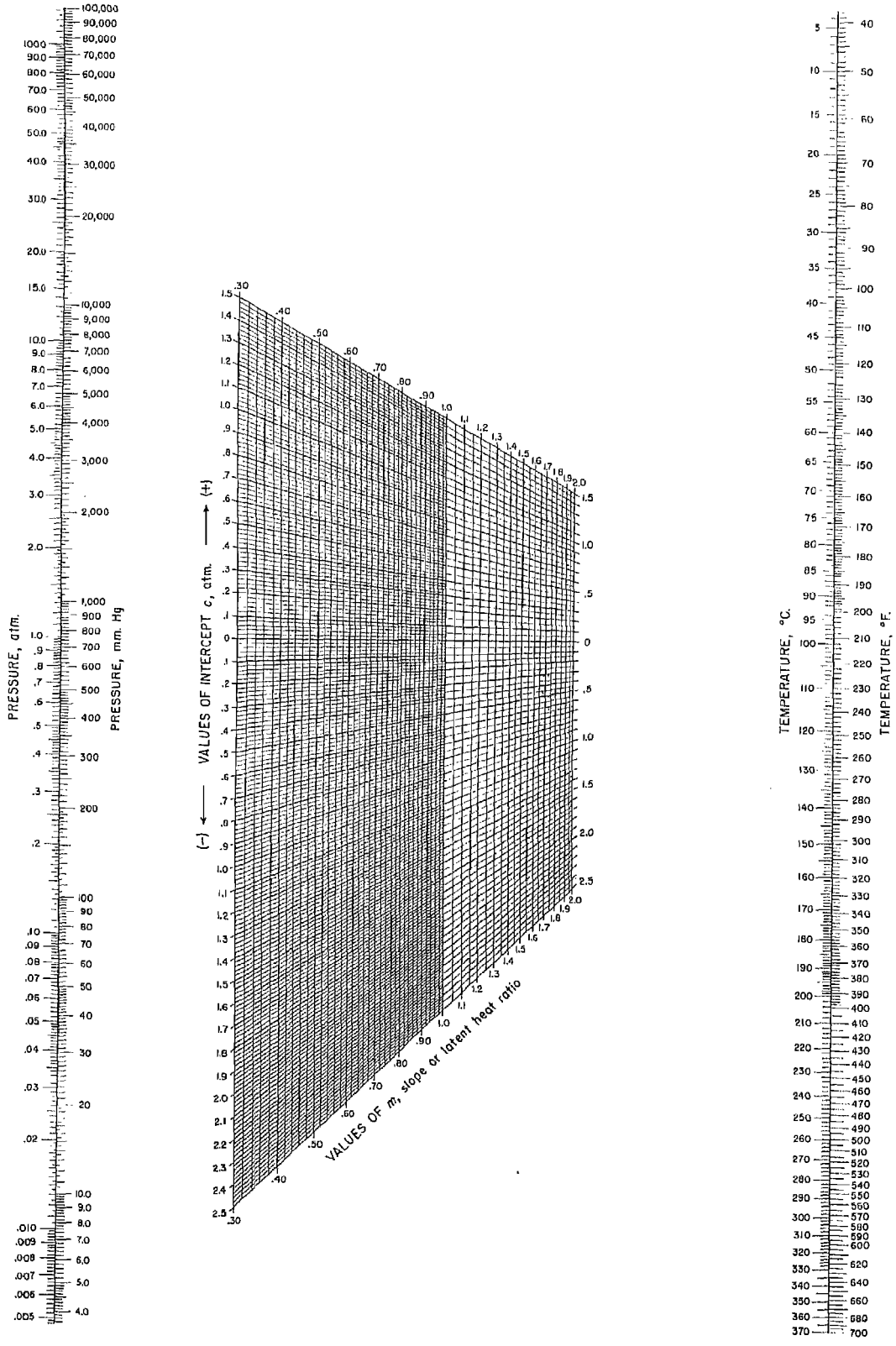


Fig. 3. See opposite page for legend.

be used, with logarithms superimposed at any desired scale on the axes.) Reduced pressures and temperatures (30) correlate accurately by this method even for the most precise data yet reported.

Vapor Pressure Nomogram. Figure 3 gives the vapor pressure function for all volatile materials up to about 370°C. and 100 atm. It has been derived by Othmer and Maurer (38) from the reference substance plot and the basic equation above. Two logarithmic scales are erected vertically, a distance D apart. The left scale, corresponding to the pressure, P, is calibrated logarithmically from bottom to top. The right scale is first calibrated logarithmically from top to bottom for values of P', the vapor pressure of water. Against these values are made the final calibrations of temperatures T in both degrees Centigrade and degrees Fahrenheit.

A pivot point must be located between the two scales for each compound. A straight line through this point intersects the left scale at a vapor pressure corresponding to the temperature indicated by the intersection with the right scale. The position of this pivot point depends on values of m and of C in the equation. Single pivot points may be labeled for each compound; but for a general nomogram there are too many such points for individual location. It is therefore necessary to establish a system of coordinates or grid by which any point may be located.

As a first step, it can be shown that different compounds having the same value of m have pivot points on the same vertical line. The value of m thus determines the relative distances of the pivot point from the two scales. Each value of C may be shown to be represented by one of a sheaf of lines through the point on the right scale when the vapor pressure of water is 1 atm. and the temperature is 100°C. An angular grid-work is thus established for locating values of m and C for any number of compounds, using the parallel vertical lines of different values of m and the sheaf of lines of different values of C. This grid defines the basic equation and interrelates directly values of temperatures, vapor pressures, molar latent heats m, and the constant C. Values of m and C for locating individual pivot points for each substance are obtained in one of four ways:

(*1*) Values of C and of m are tabulated for the compounds listed in Table I, and for many more in reference (38). These give immediately the pivot point at the intersection of the corresponding vertical line of m and the cross line of C.

(*2*) For other compounds, lines joining the corresponding points on the left and the right axes are drawn for values of vapor pressure at two temperatures. If vapor pressures at several temperatures are known, several such lines may be drawn to obtain the pivot point, and thus casual mistakes are avoided. The intersection gives the pivot point. (Incidentally, it also gives the values of the molar latent heat ratio m—from the vertical line. Thus, the latent heat may be calculated at any temperature. It also gives the value of C in atmospheres for use in the equation, if desired.)

(*3*) If the latent heat is known, the molar latent heat is calculated, and that for water is also obtained at the same temperature, so that the ratio m is found. The normal boiling point (or other single vapor pressure point) must also be known; and a single line connecting the corresponding values on the two scales is drawn. The

Fig. 3. Vapor pressure nomogram for materials at different temperatures. To use: (*1*) the values of m and C are found from the table, or from experimental values of vapor pressures at two points, or at one point and the value of latent heat; (*2*) these values of m and C locate a point on the grid, through which (*3*) a line is drawn to intersect on the left scale the vapor pressure value corresponding to the temperature value intersected on the right scale.

intersection of this line with the vertical m line at the determined value gives the pivot point, and the value of C for use in the equation.

(4) If data for two vapor pressures, or for one vapor pressure and the latent heat are known as in (2) or (3), values may be substituted in the basic equation $\log P = L/L' \log P' + C$ and solved algebraically for the values of m and C, which determine the pivot point.

Although values of C in other units than atmospheres are listed in Table I *for use in the equation*, the nomogram is based on values in atmospheres. Values of pressure may be read directly on the left scale in millimeters of mercury, or calculated in other units, however, without other adjustment.

The pivot points on a nomogram for all hydrocarbons, either straight-chain, branched or cyclic, fall on a straight line (55). To prevent confusion in using Fig. 3, this *hydrocarbon line* has not been drawn, but it may be drawn across the center grid from the point on the top where $m = 0.445$ and $C = +1.5$ to the point on the bottom where $m = 1.47$ and $C = -2.5$. (The equation of this line across the central grid is $C = -3.90m + 3.24$.) Thus, for any hydrocarbon, only one value of vapor pressure (for example, the boiling point) is necessary since the intersection of the corresponding line between the scales with this hydrocarbon line will be the pivot point. Alternately, a single latent heat value, giving the m line, will also indicate the pivot point for the compound by intersection with the hydrocarbon line.

Other liquids—or solids having vapor pressures in the indicated range at the temperatures covered—may also have their vapor pressures indicated on this nomogram. If values of vapor pressure are known at two temperatures, the two corresponding lines are drawn on Figure 3; and their intersection will be the pivot point for this material; its values of X and Y may be read and tabulated.

Extent of Vapor Pressure Function. Usually the vapor pressure function of a liquid as defined by the Clausius-Clapeyron equation, and as correlated by the reference substance equation and plot or nomogram, extends throughout the entire range between the triple point and the critical point.

Below the triple point, the slope of the vapor pressure line of the solid represents a function of the heat of *sublimation*, that is, that required to pass from the solid to the vapor stage. The relative steepness of this curve (or straight line on the logarithmic plot) is due to the fact that the heat required to change a mole of the condensed phase into a mole of vapor must include the heat to melt as well as the heat to vaporize. The sum of these heats is called the *heat of sublimation*, which may be found from the slope of the vapor pressure line of the solid. The difference in the slopes of vapor pressure of solid and of supercooled liquid may readily be found; and this difference multiplied by the latent heat of the reference substance at the same temperature indicates the heat of fusion of the liquid or the heat of melting of the solid.

Vapor pressures, by definition, discontinue at the critical point. There also may be for some relatively few compounds a discontinuity in the vapor pressure relation at other particular temperatures (indicated most noticeably by a break in the straight line of a plot such as Figure 2). This is due to some change in the chemical structure of the liquid. Thus, for example, a material that changes its polymeric form, or that goes through some transition point of chemical rearrangement (for example, sulfur), will have some heat effect associated with such a transition and hence with the latent heat and the slope of vapor pressure line.

In dealing with the vapor pressures of solutions of nonvolatile substances in a

volatile liquid, the vapor pressure of the liquid out of a solution of given concentration is markedly reduced or, as often expressed, the boiling point is elevated. The slope of the line represents the total heat involved in the escape of a mole of the liquid to the vapor phase; and it is the heat of vaporization plus the heat of "un-solution," as it were, often called the heat of dissolution of the liquid from the solid, that is, the negative heat of solution. If there is a positive heat of dissolution, the slope is greater than that of the vapor pressure line for a pure liquid; if a negative heat of dissolution, it is less. In either case, there may readily be determined the value of the heat of solution from the values of the vapor pressure, if these are known only at any two temperatures and are plotted by the system above indicated.

The vapor pressure of the liquid from the solution varies also with the concentration of the nonvolatile solute. This is of great importance in many technical applications, such as evaporation (*q.v.*). The higher the concentration of the solute, the greater the reduction in the vapor pressure; this is limited by the solubility of the solute in the solvent. Nevertheless, the same laws and method of plotting may be utilized for each different concentration of solution. A special method has also been devised by Othmer and Silvis (41) for plotting the boiling-point elevation directly.

Similarly, there is a vapor pressure function for water out of hydrates and for various other volatile materials out of similar loosely bound compounds. These functions follow the same laws and may be plotted to give the same curves, or straight lines on the logarithmic method of plotting (29), as the usual vapor pressure phenomena.

Othmer and White (46) have discussed the solubilities of gases in liquids and have shown that these values of amounts dissolved, as dependent on temperature and amount in the gas phase, may better be considered, conversely, as partial pressures of the gases out of solutions of fixed concentration. Such a method of expression then follows exactly the vapor pressure concept; the same methods of correlating may be used. Heats of solution may also be determined from the slopes of the lines, and problems in gas absorption may be simplified.

Likewise, the adsorption of a vapor (or of a permanent gas) by a solid, such as activated carbon, may be expressed best (37,40) as a vapor pressure relation of the vapor or gas out of the solid that has adsorbed thereon a fixed amount of the vapor or gas. Heats of adsorption may also be considered and determined.

Binary Solutions

The several aspects of vapor pressure discussed above are known to be directly comparable for binary solutions wherein both liquids are volatile. In this case it is often desirable to express vapor pressure not only as the total pressure exerted by the system, but also as partial pressures of the individual components. It is often convenient to use the reference system of plotting for either total or partial pressures, and it may be desirable to use one of the pure liquids themselves as the reference material.

The partial pressure of one constituent will have a different vapor pressure relation with temperature than if it were pure, owing to the effect of the vapor pressure of the other constituent. Hence it is necessary to specify another function; that is, the *vapor composition*, y, in mole fraction or per cent of the more volatile component in the vapor in equilibrium with the liquid of composition x.

The most simple, and useful, plot involving vapor composition is $y = F(x)$ in the so-called x,y plot at constant total pressure of vapor composition versus liquid com-

position, as in Figure 4(*b*). Here the 45° diagonal indicates the equivalence of composition of the two phases. An older expression is the plot of Figure 4(*a*), also at constant total pressure, of temperatures of boiling and of condensing to give the familiar boiling point and dew point for any given composition. Any horizontal line between the two curves intersects the equilibrium composition conditions between the two phases at the boiling or condensing temperature.

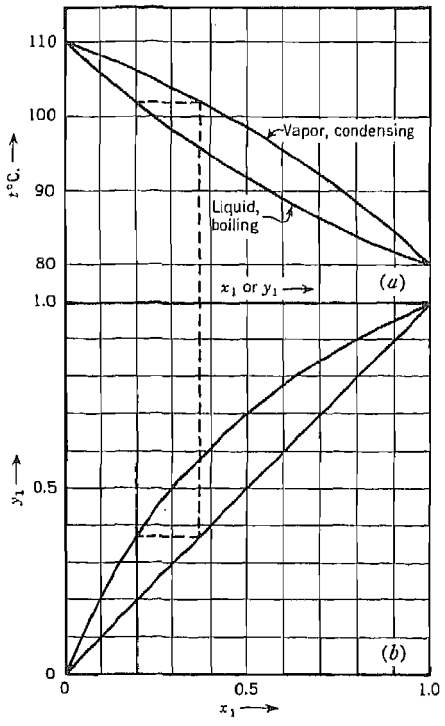


Fig. 4. Benzene(1)–toluene(2) mixtures. (*a*) Vapor-liquid curves. Upper or vapor line is the dew-point curve; lower or liquid line is the boiling-point curve. Horizontal dotted line between the two curves shows the phase equilibria at a given temperature (102°C.); this distance between the curves is equal to the horizontal distance in (*b*) between the curve and the diagonal for the same value of x_1. (*b*) Vapor composition in equilibrium with liquid composition expressed in mole fractions benzene—the more volatile (x,y curve).

A compilation of reported data of vapor-liquid equilibrium has been made by Chu (7), from which many of the data following have been taken.

A correlation of total pressures throughout the entire range up to the critical is more difficult for binary solutions because of the much more involved relations of P, T, x, y data and their representation in the critical range, as compared to the relatively simpler P, T data for a pure liquid. One usual method of such presentation is shown in Figure 5, wherein isotherms are plotted on a pressure versus composition plot. Gilmont, Roszkowski, and Othmer (15) showed that a logarithmic, reference substance plot could be made using reduced temperatures and pressures that present all P, T, x, y data for most systems as a sheaf of straight lines intersecting at the point 1,1. In this figure, the line of critical locus gives the pressure and temperature rela-

tion for the critical conditions for all compositions of the binary. The line of cricondentherm locus defines those pressures at different compositions at which the isotherms reached their maximum composition. The line of maximum pressure locus represents the envelope enclosing the isotherms for the maximum pressure of the lines of constant composition under any variable conditions of pressure and temperature.

Other useful functions that follow directly from the vapor pressure relations are the equilibrium constant $K = y/x$, the relative volatility $\alpha = y(1 - x)/x(1 - y)$, and the activity $\gamma = Py/p^0x$, where P is the total pressure, and p^0 is the vapor pressure of the more volatile component in the pure state.

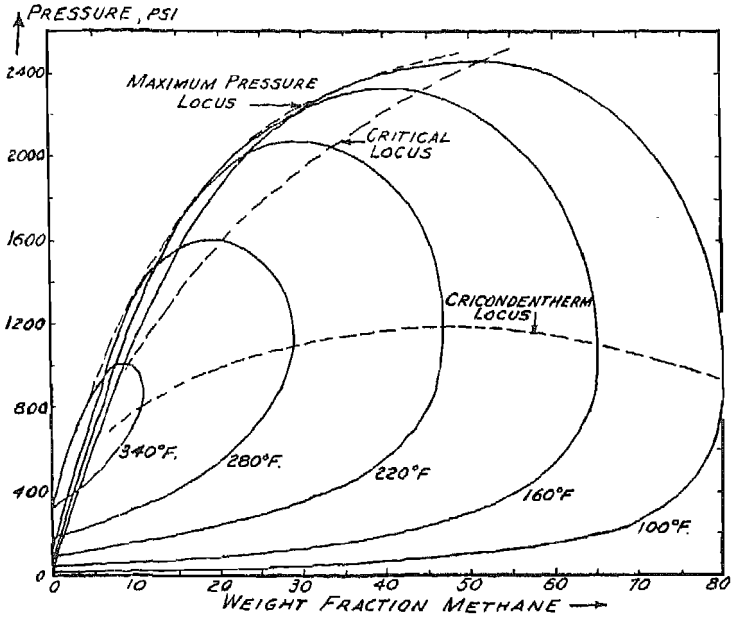


Fig. 5. Total vapor pressure in system methane–*n*-pentane against weight fraction methane (15). Isotherms are shown; the right side of each loop represents a vapor or dew-point curve, the left side a liquid or boiling-point curve.

All of these functions may be correlated by the same method of reference substance plotting on logarithmic paper against the temperature scale derived from the vapor pressure of a reference liquid, as indicated above. They may also be correlated directly by another method developed by Othmer and Gilmont (35,36) which does not use a reference substance. This is a direct logarithmic plot of the function against the total pressure on the system, and gives another system of straight lines, the slopes of which are also ratios of latent heat expressions.

CLASSES OF BINARY SYSTEMS OF VOLATILE LIQUIDS

There are several types of binary mixtures, classified as to the composition of vapors in equilibrium therewith. Usually, the compositions are expressed at a constant pressure, atmospheric being the most common. In some cases, data for theoretical uses are also presented at constant temperature with variable pressures.

Ideal. In the perfectly ideal solution of two materials, the composition of the

vapors that are in equilibrium with the liquid would be calculable directly from Raoult's law (in this case $\gamma = 1$). The boiling point would also always be between the boiling points of the two pure liquids. Comparatively few binary mixtures, except those of close homologs, fall in this class. The solution of benzene and toluene is about as close to an example of an ideal solution as any solution of actual materials. This is shown in Figure 4. Other nearly ideal solutions are of related straight-chain hydrocarbons of close boiling points.

Concavity Upward. For most mixtures there is slight association of one or both liquids, or other reasons for deviations from Raoult's law. Thus, for example, in the case of water and acetic acid, a curve such as that shown in Figure 6 is obtained (it

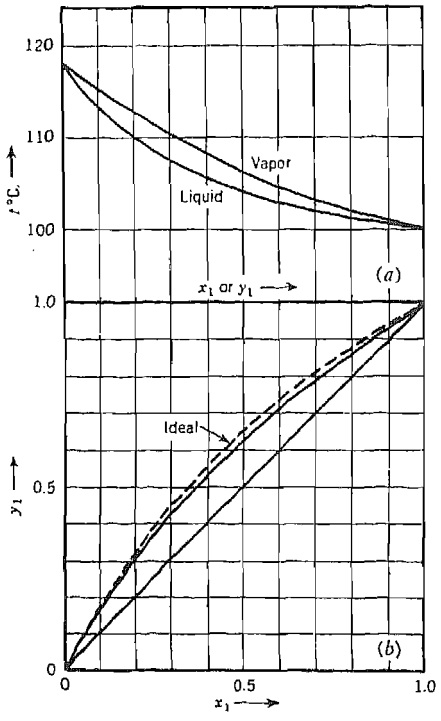


Fig. 6. Water(1)-acetic acid(2) mixtures. The dotted line in (*b*) indicates the calculated value of the vapor composition from the assumption of ideal solutions, utilizing Raoult's law. Near the upper corner, the actual vapor composition curve is concave upward.

is expressed in terms of water, the more volatile). The corresponding curves calculated from Raoult's law are given to show the extent of deviation from ideality. The boiling points of all mixtures fall in between the boiling points of the pure compounds; but mixtures high in the more volatile component may approach its boiling point. Another similar example is acetone and water at 1 atm. shown in Figure 7; in this case also there is a decided concavity upward in the curve.

Minimum C.B.M. There are also several types of mixtures called **azeotropic** or **constant-boiling mixtures,** or simply C.B.M. (Azeotropic comes from Greek words meaning "to boil unchanged.") In the plot of the vapor composition versus the liquid composition, if the curve crosses the 45° diagonal, the vapor and liquid have the same

composition; that is, at that point there is no change in composition, and distillation in the ordinary sense will not accomplish a separation. On the boiling point diagram this is shown by a dip of the curve, which meets the dew-point curve at the C.B.M. Both curves drop below the temperature of boiling of the more volatile component; or both curves rise to intersect at a C.B.M. with a temperature higher than the boiling point of either pure compound.

The most common such mixture is a **minimum constant boiling mixture** such as that of acetone and water at elevated pressures, as shown in Figure 7. A simple

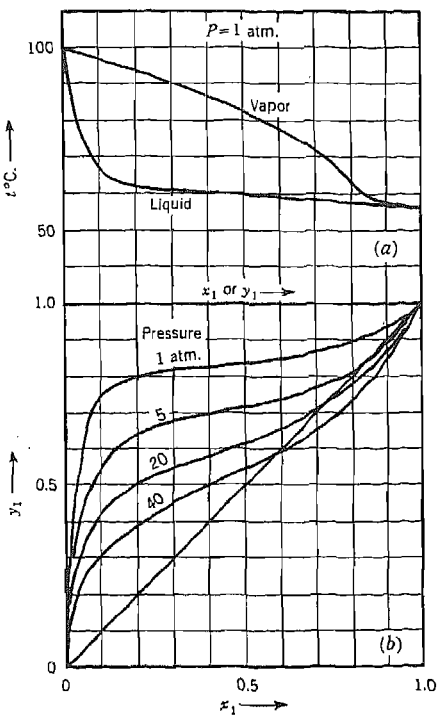


Fig. 7. Acetone(1)–water(2) mixtures. Several x,y curves are shown in (*b*) at different pressures. A homogeneous minimum-boiling azeotrope appears when the curve crosses the diagonal. The first one is at approximately 2.5 atm.

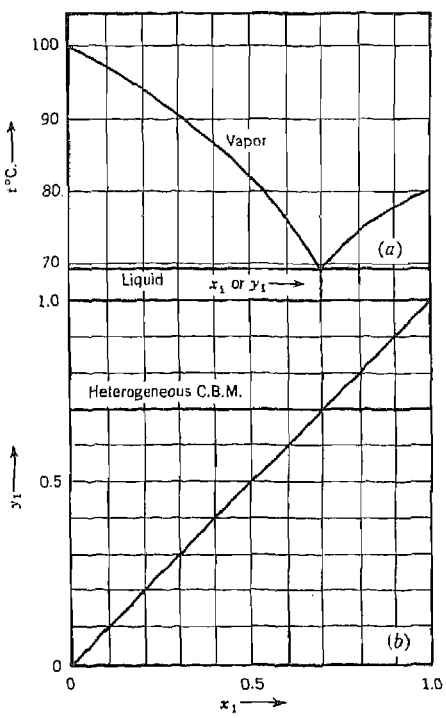


Fig. 8. Benzene(1)–water(2) mixtures. An example of a heterogeneous azeotrope in a system of practically complete immiscibility.

example at atmospheric pressure is ethyl alcohol and water; see Vol. **1**, p. 269, and Fig. 16. Here it is found that the composition at approximately 10 mole per cent ethyl alcohol is such that there is no difference between liquid and vapor; and no simple rectification by distillation is possible. There are numerous other pairs of liquids in this class.

The x, y curve for ethyl alcohol and water in Figure 16, is for atmospheric pressure; but if the data are plotted for lower pressures, the composition of the C.B.M. moves up the 45° line and finally disappears at 100%. At pressures below about 75 mm. there is no C.B.M. Similarly, the curve for acetone and water, which at atmospheric pressure has only a slight concavity, at higher pressures becomes more and more concave upward, as shown in Figure 7. Above about 2.5 atm. pressure, a C.B.M.

appears; and its composition (in acetone) becomes less as pressure rises. Thus it is felt that there is no sharp demarcation of kind for mixtures having C.B.M. from those which do not; and many may be regarded as simply deviating more and more from the ideal at higher pressures until finally a C.B.M. appears. There are some mixtures, *for example, acetic acid and water (42,43), that exhibit properties that are far from* ideal, and yet never show a C.B.M. up to pressures in the critical range. On the other hand, there are other mixtures that show C.B.M.'s (of varying composition) throughout the entire pressure and temperature range investigated.

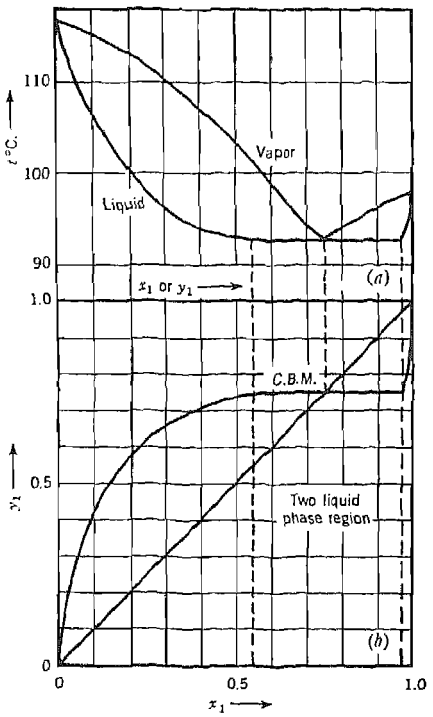


Fig. 9. Water(1)-1-butanol(2) mixtures. An example of a heterogeneous azeotrope in a system of partial immiscibility.

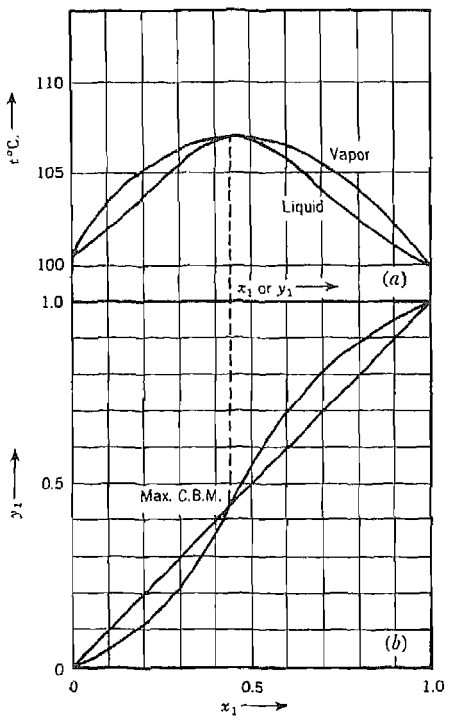


Fig. 10. Water(1)-formic acid(2) mixtures. An example of a homogeneous maximum-boiling azeotrope, indicated in (*b*) by *x,y* curve intersecting diagonal from beneath.

Immiscible and Partially Miscible Mixtures. The vapor-liquid equilibria for immiscible liquids are analogous to the eutectic mixtures in liquid-solid equilibria. For completely immiscible liquids there would be a single vapor composition (and single boiling point) for all finite ratios of amounts of the two liquids, that is, all liquid compositions. Such a system has what is called a *heterogeneous azeotrope* to distinguish it from the *homogeneous azeotrope*, a single liquid phase, both boiling and condensing. The heterogeneous azeotrope has a minimum C.B.M. at the point where the horizontal *y* line of the *x*, *y* diagram crosses the 45° line. The vapor pressure of each component *acts substantially independently of the other*; and the total pressure for the two liquid phases is equal to the sum of the vapor pressures of the two pure components. This higher pressure than for either naturally corresponds to a lower boiling point of the mixture.

The relative solubilities of benzene and water are sufficiently small so that a system of these two liquids very closely approximates one of complete immiscibility. Its vapor-liquid composition curve is shown in Figure 8 and consists of a horizontal line of the same vapor composition throughout the entire liquid range between the solubility of water in benzene (less than 1%) on the right, and benzene in water on the left (also less than 1%). The entire relationship can be calculated from the vapor pressures of the pure components and the molecular weights.

It is much more common to find mixtures of liquids that exhibit partial solubility in each other. Thermodynamically, there must always exist some partial solubility, even though this may be so small as to be considered zero for practical purposes. Thus the system water and 1-butanol shown in Figure 9 is an example of partial immiscibility. Again there is a horizontal portion of the x, y curve over which the vapor composition is constant; and this crosses the diagonal. There is thus a heterogeneous azeotrope or minimum constant boiling mixture at this point. The regions of partial miscibility are to the left and right of the two-phase liquid section, which defines the straight, horizontal section of the vapor composition curve. In these miscible parts, the curve resembles that of a homogeneous azeotrope of minimum boiling point. If the pressure is increased, the boiling temperatures become higher; and for butanol and water there is complete miscibility. The horizontal section of the vapor composition curve becomes less and less wide; and the system finally loses this characteristic heterogeneous azeotropy—although it continues to have a homogeneous C.B.M.

If the degree of mutual solubility of comparable systems decreases (for example, in plots for systems with water of alcohols of increasing number of carbon atoms, and hence decreasing solubility), the curves show at atmospheric pressure: (*1*) for methanol, a concavity upward; (*2*) for ethyl alcohol a minimum C.B.M.; (*3*) for 1-butanol, a heterogeneous C.B.M. with a horizontal line of fixed vapor composition over a part of the range; and (*4*) for higher alcohols, an increasing range of the immiscible section with a greater length of the straight and horizontal section of the vapor composition curve.

Thus it follows that all except ideal systems seem related; and differences between different systems are really not of kind, but of degree of increasing deviation from ideality in exhibiting curves from: (*1*) concavity upward, through (*2*) homogeneous minimum C.B.M. to (*3*) heterogeneous C.B.M. This variation may be from lower pressures and temperatures to higher, or else in the reverse direction; and seems to be related to the mutual solubility characteristics of the two liquids. (The entire range is not usually experienced for most pairs of liquids.)

It is interesting to note that only those systems that may be called *completely* and *ideally* miscible, and those that are *completely immiscible* may have their vapor compositions calculated from their vapor pressures with any accuracy.

In some rare systems a curve may cross the 45° line to form a C.B.M., and at a lower point to the left enter the horizontal stretch characteristic of the immiscible range (like a peritectic mixture for liquid-solid equilibria). Here there are exhibited both the homogeneous C.B.M. and the heterogeneous phenomenon of two-phase liquid and vapor condensate, but in this case the vapor composition of the C.B.M. lies outside the range of concentrations when there are two liquid phases. Such an example is the system methyl ethyl ketone and water (33,34).

Steam Distillation Phenomenon. There are other heterogenous C.B.M.s than those including water. Water, however, is largely immiscible with many organic

liquids, and it is said to "steam distill" with them due to the additive vapor pressures of these immiscible combinations. Effectively, the temperature of boiling of the liquid is reduced; and even if it is otherwise relatively high-boiling, it may be swept along in spite of its low partial pressure by the higher and additive vapor pressure of water at a temperature low enough to prevent the decomposition which otherwise might result.

Maximum Constant Boiling Mixtures. These are relatively few and they are always homogeneous. The reason for their formation is even less subject to prediction; and appears to be due usually to an association between the components, such as a hydration of volatile acid molecules by water; for example in the case of the respective binary mixtures with water of formic, nitric, and hydrochloric acids. A variation of the molecular species thus indicates a change in the relative pressures. Pairs of organic liquids in this class are also known; and studies of the possible chemical and molecular structures might be interesting.

The x, y, and boiling-point curves are shown for a typical example, formic acid and water, in Figure 10 (32), the x, y curve necessarily having the two sections in reversed positions as compared to those for a mixture having a minimum C.B.M. Here again it follows, however, that rectification by distillation of a mixture to either side of the C.B.M. would give only the one pure component (in either case, the *heads* product) with the C.B.M. as the other product (in this case the *bottoms* product) of a still, even if it were of infinite length.

CORRELATION OF VAPOR-LIQUID EQUILIBRIA

Correlation Through a Range of Pressures. Methods of plotting and correlating P, T, x, y data are indicated above utilizing the vapor pressure of a reference substance as a means of deriving the temperature scale. The slopes of the vapor pressure lines for different liquid compositions may be used to calculate the vapor composition curve directly (29); and the method, which is thermodynamically sound within the minor limitations already indicated, may also be used in reverse to obtain vapor pressure data for an entire pressure range if accurate data on vapor-liquid equilibria are available at two pressures.

Variations of these methods for correlating the vapor compositions of such equilibria are also available which give straight lines over wide ranges when plotted either against the total pressure (35) or against the derived temperature scale. One system that deviates greatly from ideality is that of hydrochloric acid and water. Its vapor composition curves in Figure 11 are seen to be straight lines by this method. This fact adds to the confidence that can be given to the experimental data. Another very sensitive function widely used in correlation of vapor-liquid equilibriums is the activity coefficient, γ. It is usually associated with and derived from vapor pressure data, but it may also be determined for the hydrochloric acid and water system from precise electromotive force measurements. The data of Åkerlöf and Teare (1) are plotted in Figure 12. The lines are straight, as they should be from the thermodynamic considerations on which the plots are based, and the slopes are equal to the ratio of the heat of solution to the latent heat of water. Thus activities from either vapor pressure or other experimental techniques may be correlated per se or used as a means of correlating or predicting vapor composition data.

Correlation at a Single Pressure or Temperature. In few cases are data available over a range of temperatures and pressures. Therefore methods are needed that are applicable to data taken at a single pressure (3,11,16,39,49). The fundamental basis

of most theoretical methods of correlation is the Gibbs-Duhem equation, which is a consequence of the first and second laws of thermodynamics applied to multicompo-

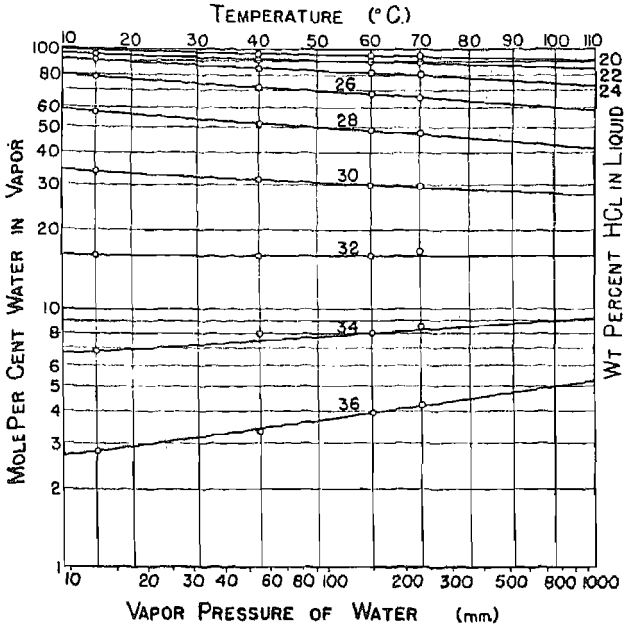


Fig. 11. Logarithmic plot of the vapor composition (y) of solutions of hydrochloric acid in water vs. a temperature scale derived from vapor pressure of water (35). The straight lines are for constant liquid compositions.

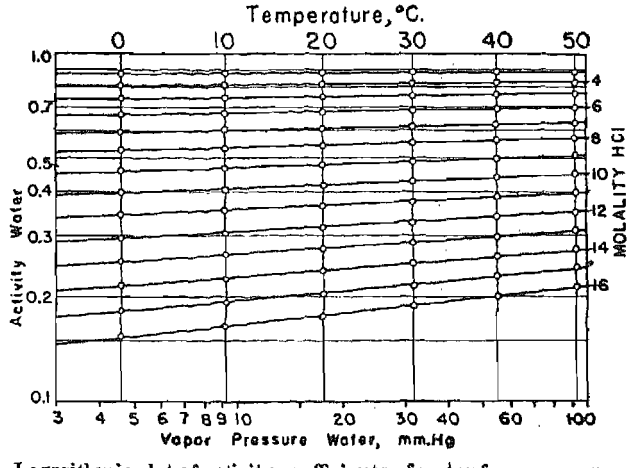


Fig. 12. Logarithmic plot of activity coefficients of water from aqueous solutions of hydrochloric acid, plotted against the temperature scale derived from the vapor pressure of water (35). The straight lines show the variation of activity coefficients with temperature at constant liquid compositions.

nent systems; and is stated in terms of activity coefficients at constant temperature and pressure:

$$x_1 d \log \gamma_1 + x_2 d \log \gamma_2 + x_3 d \log \gamma_3 + \ldots = 0$$

This applies to a homogeneous phase in equilibrium consisting of two or more independent components in which x_1, x_2, etc. are liquid compositions. The correlation of the equilibrium between vapor and liquid makes use of another thermodynamic principle from Gibbs; that is, the pressure, temperature, and chemical potential of each component must be the same in both the liquid and vapor phases. Chemical potential is defined as the partial pressure (or more accurately by *fugacity*, which is the thermodynamically corrected partial pressure). Thus the activity coefficient in the liquid may be defined in terms of the partial pressure in the vapor phase (assuming that the vapor obeys the ideal gas law) as stated previously:

$$\gamma_1 = Py_1/p_1^0x_1$$

This equation is expressed for component 1, but is equally applicable to the other components. Py_1 is the partial pressure of component 1 in the vapor phase, and $p_1^0x_1$ is the partial pressure according to Raoult's law, that is for an ideal liquid solution. Thus, the activity coefficient is seen to be the direct ratio of the actual partial pressure of the component in the vapor phase to the ideal partial pressure according to Raoult's law; in other words, it is a measure of the *nonideality* of the system. For ideality $\gamma = 1$. Positive deviations from ideality give activity coefficients greater than unity (positive logarithms) and negative deviations give activity coefficients less than unity (negative logarithms). In applying these last two equations to the correlation of vapor-liquid equilibria, it should be emphasized that the assumptions made in their derivation will not necessarily allow exact results in their use; however, in most cases at ordinary conditions the errors due to these assumptions are much less than those due to experiment. For extreme conditions, such as high pressure, fugacities are employed instead of partial pressures to account for nonideality in the *vapor* phase. Thus, whereas nonideality in the *liquid* phase is quite common, that in the *vapor* phase may be generally neglected.

Integrated Forms of Basic Equation. Since the Gibbs-Duhem equation is in differential form, methods needed to perform the integration have been discussed (3,39,49). Graphical methods usually give accurate results, when no analytical function can be found to satisfy the experimental data. Two popular methods are the more or less empirical analytical integrations of van Laar and Margules. The method of van Laar, based on some definite assumptions, gives:

$$\log \gamma_1 = Ax_2^2\Big/\left(\frac{A}{B}x_1 + x_2\right)^2 \qquad \text{and} \qquad \log \gamma_2 = Bx_2^2\Big/\left(x_1 + \frac{B}{A}x_2\right)^2$$

The method of Margules, based on other specified assumptions, gives:

$$\log \gamma_1 = (2B - A)x_2^3 + 2(A - B)x_2^3 \text{ and } \log \gamma_2 = (2A - B)x_1^3 + 2(B - A)x_1^3$$

These are for binary systems; multicomponent systems yield greater complexities. The constants A and B are specific for each system and are determined from the experimental data in a variety of ways. When a large number of points on the curve are known, some method of curve fitting, either analytical or graphical, is usually employed to obtain the value of the constants. When only a single point on the vapor-liquid equilibrium curve is known, such as an azeotrope, the constants in the last two equations may be solved for simultaneously.

Depending upon the system, the closeness of the representation may be better with the van Laar than the Margules equation, but the van Laar equation has the

disadvantage that it does not permit a maximum or minimum point due to its particular mathematical form. Since many systems exhibit maximum or minimum points, the Margules equation must then be used. When data are known to a high degree of accuracy, it is possible to extend the van Laar or Margules equations to a larger number of constants. In this case the Margules equation is found more convenient.

If experimental data fit either of these equations, this adds to the confidence with which they may be given credence, although there is no assurance against systematic errors, due to the empiricism and assumptions of this approximate integration.

Relative Volatility. Relative volatilities are defined and related to activity coefficients as follows:

$$\alpha_{1,2} = \frac{y_1 x_2}{x_1 y_2} = \frac{\gamma_1 p_1^0}{\gamma_2 p_2^0}$$

The subscripts of $\alpha_{1,2}$ indicate that it is the relative volatility of component 1 with respect to 2 and may be applied to a multicomponent system as well as to a binary.

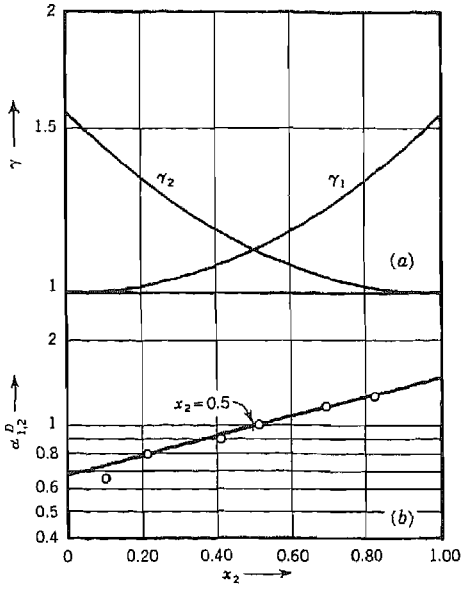


Fig. 13. Carbon disulfide(1)-chloroform(2) mixtures. (*a*) Logarithmic plot of activity coefficients. The lines cross at $x_2=0.5$. (*b*) Logarithmic plot of relative volatility deviation, $\alpha_{1,2}^{D}$ of carbon disulfide with respect to chloroform. The straight line passes through the value of 1.0 at $x=0.5$, so that the area of the triangle above the horizontal axis equals that of the one below.

For an ideal solution, the relative volatility is equal to the ratio of the partial pressures of the two liquids, and this is independent of the composition at a given temperature. At constant pressure, the ideal relative volatility varies somewhat with composition due to the changing boiling point. Obviously, if the system were ideal, the entire vapor compositions would be immediately calculable from the last equation for every value of liquid composition if the individual vapor pressure curves for the two components are known.

A relative volatility *deviation* is employed, defined as:

$$\alpha^{D}_{1,2} = \frac{\alpha_{1,2}}{\alpha^{I}_{1,2}} = \frac{\gamma_1}{\gamma_2}$$

where $\alpha^{I}_{1,2}$ is the ideal relative volatility. For an ideal solution $\alpha^{D}_{1,2}$ equals unity for all compositions at any temperature or pressure. Thus, if vapor-liquid equilibrium data are recalculated in this form, an ideal system is indicated when all compositions show

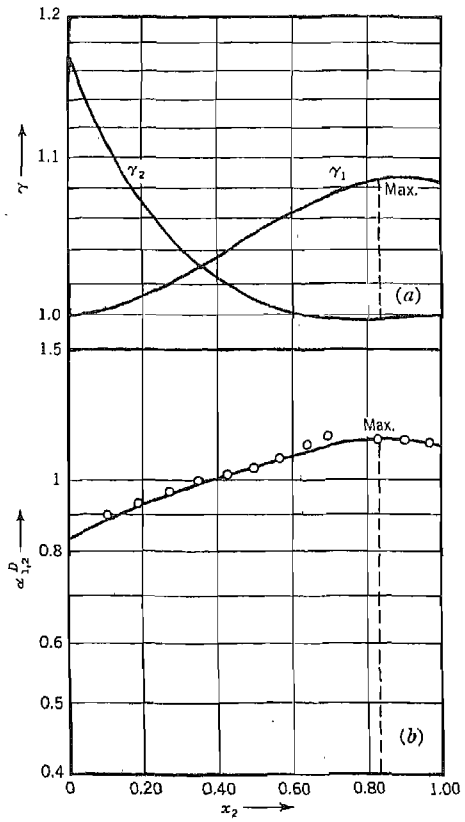


Fig. 14. Carbon tetrachloride(1)–heptane(2) mixtures. (*a*) Logarithmic plot of activity coefficients, showing maximum and minimum at $x_2 = 0.83$. (*b*) Logarithmic plot of relative volatility deviation of carbon tetrachloride with respect to heptane, showing maximum at same composition.

$\alpha^{D}_{1,2} = 1.0$. Such is the case, for example, for the system of propylene bromide and ethylene bromide; $\alpha^{D}_{1,2}$ is equal to unity everywhere except at the extreme ends of the composition range. For convenience, logarithms of relative volatility and activity coefficients are used. Thus:

$$\log \alpha^{D}_{1,2} = \log \alpha_{1,2} - \log \alpha^{I}_{1,2} = \log \gamma_1 - \log \gamma_2$$

The simplest deviation from ideality yields a straight line of finite slope when $\log \alpha^{D}_{1,2}$ is plotted against x_2. For positive deviations from Raoult's law, the slope will be positive and for negative deviations the slope will be negative. From the Gibbs-

Duhem equation it may be shown that this straight line must pass through unity (log 1 = 0) at x = 50 mole per cent, so that the area above the X-axis is equal to the area below the X-axis. For this case it also follows that the activity coefficients can be expressed by a single constant A (here $A = B$) in the van Laar or Margules' equations which are then identical; and the activity coefficient curves are symmetrical, half parabolas. The above conditions for the system carbon disulfide–chloroform are shown in Figure 13 as plots of log γ_1 and log γ_2 vs. x_2, and of log $\alpha_{1,2}^D$ vs. x_2.

Usually log $\alpha_{1,2}^D$ plots as a curve against x_2; but, the Gibbs-Duhem relationships still requires that the area under the curve and above the X-axis be equal to the area below the X-axis and above the curve. Practically, these curves may be treated as

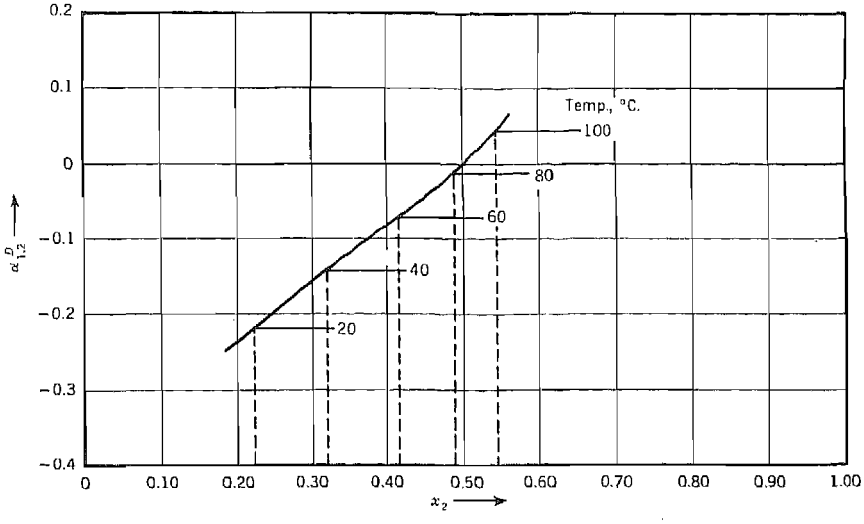


Fig. 15. Logarithmic plot of relative volatility deviation of ethyl acetate with respect to ethyl alcohol, to show the variation of azeotropic composition with respect to azeotropic temperature.

parabolas; and the resulting relationships for the activity coefficients obey the Margules equations. Figure 14 for the system carbon tetrachloride–heptane shows this when a maximum appears in the plot of log $\alpha_{1,2}^D$ vs. x_2; and a corresponding maximum or minimum also appears for each component at the same composition in the log γ vs. x_2 plots.

When the data are known with sufficient accuracy and the variation from ideality is considerable, the log $\alpha_{1,2}^D$ vs. x_2 plot may be more accurately defined by a power series of degree higher than two. Thus for water–dioxane the data require a *fifth*-order power series for the log $\alpha_{1,2}^D$ curve. This gives a sixth-order equation for the activity coefficient curves, but since the first-order term is missing, the same number of independent constants, namely, five, must be determined to define the curves.

Azeotropic Systems. For homogeneous systems the azeotrope occurs where $\alpha_{1,2} = 1$, or log $\alpha_{1,2} = 0$; thus, from the definition of relative volatility:

$$\log \alpha_{1,2}^D = -\log \alpha_{1,2}^I = \log (p_2^0/p_1^0)$$

Plotting the logarithm of the vapor pressure ratio of the components on the log $\alpha_{1,2}^D$ graph gives the azeotrope at the intersection of the curves. If log $\alpha_{1,2}^D$ does not vary

with temperature, which may be assumed for short ranges, the change of the azeotrope with respect to temperature and pressure may be predicted by plotting the appropriate values of log $\alpha^{I}_{2,1}$ at each temperature, and determining the point of intersection with the curve, log $\alpha^{D}_{1,2}$. For example, the system ethyl alcohol – ethyl acetate is shown in Figure 15 with several values of log $\alpha^{I}_{2,1}$ plotted for the indicated temperatures intersecting the curve log $\alpha^{D}_{1,2}$. The points of intersection correspond to the respective azeotropic compositions. (A more simple correlation by Othmer and Ten

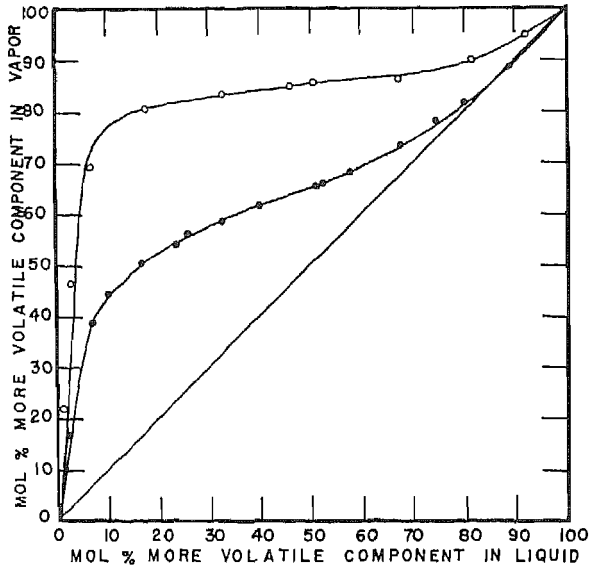


Fig. 16. Vapor-liquid equilibria for two nonideal binary systems: acetone(1)-water(2) (open circles) and ethyl alcohol(1)-water(2) (black circles). The points indicate the accepted experimental data; the lines are from calculated values (39).

Eyck (44) plots logarithmically the azeotropic compositions or activity coefficients directly as straight lines versus total pressures or versus temperatures derived from the vapor pressure of a reference substance.)

Change of Activity Coefficient with Temperature and Pressure. With temperature and pressure change the Gibbs equation becomes:

$$x_1 d \log \gamma_1 + x_2 d \log \gamma_2 \ldots - \frac{V\,dP}{2.303RT} + \frac{S\,dT}{2.303RT} = 0$$

where V is the molar volume of the system, and S is the molar entropy of the system. This gives an equivalent change of γ with pressures as follows:

$$(\delta \log \gamma_1/\delta P)_{T,x} = \bar{v}_1/2.303RT$$

where $\bar{v}_1$ is the partial molal change in volume of component 1 upon mixing. Also, there is a change with temperature as follows:

$$(\delta \log \gamma_1/\delta T)_{P,x} = -(\bar{h}_1/2.303RT^2)$$

where $\bar{h}_1$ is the partial molal heat of solution of component 1 upon mixing.

For an ideal solution the volume change and heat of solution are both zero, and

the activity coefficient is unity at all values of temperature and pressure. For nonideal solutions, the activity coefficient changes only slightly with pressure until high pressures are reached; for mixtures with high heats of solution, the change with temperature is significant and corrections must be applied. However, by considering relative volatility *deviations*, it is possible to minimize these changes. Scheibel (54) has developed nomograms based on the theory of corresponding states for correcting activity coefficients at high pressures.

Use of Boiling-Point Data with Gibbs Equation. Utilizing boiling-point data at a single pressure for different liquid compositions (that is, T, x data), Othmer, Ricciardi, and Thakar (39) developed from the work of Hirata (17) and others a rigorous method of predicting and correlating equilibrium values through the integration of the Gibbs-Duhem relationship by either graphical or algebraic methods. This method is also useful for ternary systems and enables the calculation of such equilibria without tedious laboratory analyses. The vapor-liquid equilibria for any system may thus be represented readily by one or three straight lines on logarithmic paper, and then replotted in the standard (x, y) plot. This method gives excellent agreement with precise and accepted experimental data for acetone–water and ethyl alcohol-water (see Fig. 16), two systems varying widely from the ideal.

Multicomponent Systems

Multicomponent systems may be correlated by the above equations for binary systems. The complexity of the equations increases tremendously with the number of components; and the fitting of the data becomes laborious. Published data are scant for ternaries, practically nil for quaternaries, and nonexistent for higher systems. Methods have therefore been expanded from those used for binaries with simplification of constants and use of data from constituent binaries (53,56,57). Another method is based upon summing the chemical potentials of the component binaries (11); and Figure 17 shows a prediction so made in the ternary system benzene–chloroform–acetone to be relatively close to experimental values.

Petroleum Systems, Equilibrium Flash Vaporization. The most important multicomponent systems are those of petroleum crudes and fractions after distillation. The vapor-liquid equilibria become very complex, because of the many components present and their wide range of volatilities. Somewhat involved methods utilizing "key" components are used as a means of averaging out relations for definite ranges based on properties of individually important members in the range. For much work there is used the relation of boiling temperatures at a fixed pressure versus per cent vaporized, with composition in the still changing as more volatile components discharge. Ten Eyck and Othmer (55) utilized the general criterion of the boiling point of either the original sample, any fraction thereof, or any amount remaining after any desired amount had undergone the equilibrium flash vaporization (EFV) of a usual petroleum distillation. An experimental boiling point on an EFV curve need be determined at only one pressure to use this semirigorous method at any other pressure or vacuum. Analytical data for the compositions are seldom known and are not required. Design data for petroleum refining are obtained from a simple monogram; and here again, actual compositions of the fractions are unnecessary in use.

The nomogram of Figure 3, an improvement over that of ref. (55), may be used directly by drawing a line across this grid between the points $m = 0.569$ and $C =$

+1.5 at the top, and the point $m = 1.43$ and $C = -2.5$ at the bottom. (The equation of this line is $C = -4.51m + 4.11$.) This, the *petroleum mixtures* line, is the location of the pivot point for the vapor pressure of any petroleum crude or mixture; and one point of vapor pressure (from EFV or other measurements) thus defines the system throughout the entire pressure and temperature range. This line is very close indeed to the hydrocarbons line (see p. 620) throughout the useful range.

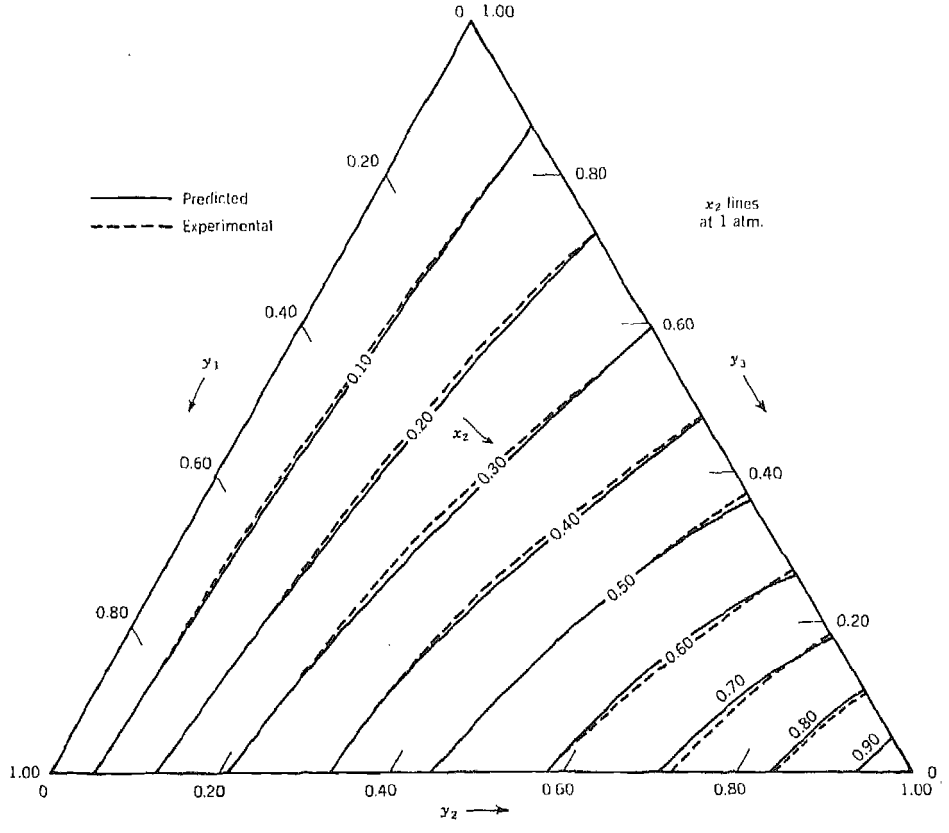


Fig. 17. Vapor-liquid equilibria for the ternary system acetone(1)-chloroform(2)-benzene(3) at 1 atm. pressure. Values of the vapor compositions of the three components are indicated on the respective sides of the triangle. The amount of chloroform in the boiling liquid which corresponds is shown by the dashed-line curves for experimental values and by full-line curves for the calculated values (11).

Experimental Determinations

The above theoretical methods of correlation and prediction of vapor-liquid equilibria should be regarded only as auxiliary to experimental determinations. There are many techniques, although some of the basic principles followed in these methods have not changed in 30 years, others not in 60 years. It is thus more advantageous to review these principles rather than to try to enumerate all of the specific individual apparatus employed. There are historical reviews by Young (59), Fowler (13), and Carney (4).

Static Method. The elementary determination of P, T, x, y, data is by the use of a static equilibrium. A mixture of the pure components in a closed vessel is placed in a thermostat and connected for pressure measurements. The vessel is thoroughly agitated until the vapor and liquid phases reach a constant composition. Connections are provided so that there may be removed for analysis samples of vapor and liquid sufficiently small that the equilibrium is not upset. If only a small vapor sample is needed and if the original liquid composition is known, a liquid sample may be unnecessary.

Although this method is simple in principle, it has many practical difficulties and is rarely used except in studies of systems at high pressures and temperatures in a bomb. Pressures are often measured with dead-weight balances employing hydraulic cylinders. Of the innumerable possible methods of analysis of the samples, only those may be used that are applicable to small samples.

Dynamic Methods, Unsteady State. In order to hasten the attainment of equilibrium and to avoid difficulties of the static method, several dynamic methods have been devised. The oldest method uses *continuous distillation at constant pressure* with samples of condensate continuously withdrawn for analysis. Care is taken to avoid superheating of the vapor, entrainment of liquid in the vapor, and rectification due to condensation. If the vapor is superheated, the equilibrium boiling temperature will read high; if there is entrainment the vapor composition will be poorer; and if there is condensation and rectification it will be richer, in more volatile component, than the true equilibrium vapor. The instantaneous equilibrium conditions of vapor and liquid composition are determined by differentiation and material balances of the data for condensate composition. A single batch distillation thus gives data from the starting liquid composition to the residual liquid composition.

An early apparatus of this type designed by Brown (2) in 1879 had a jacket around the still neck through which the vapors passed. No heat could thus be lost from the still head. This prevented rectification by contact of condensate formed with rising vapors and change of composition therein. He discarded the first vapor samples to eliminate the effect of air being purged. The method of *continuous distillation at constant temperature* may also be employed. In this case the pressure on the system is continuously adjusted while the liquid, maintained at a constant temperature, boils at a uniform rate.

When working at high pressures, any gases present may offset the equilibrium. In order to maintain constant pressure of the boiling system, the heat added to the boiler must be balanced against the heat removed by the condenser. This latter procedure is not normally employed in a continuous distillation due to experimental difficulties; but it is applied to some of the steady state dynamic methods described below.

Using a flow of inert gas, the method of *continuous evaporation* or *transpiration* was suggested by Linebarger (22) in 1895. Instead of boiling the equilibrium mixture, a stream of inert gas, passed through the mixture with intimate contact, saturates itself with the equilibrium vapor. After de-entrainment, subsequent condensation of the vapor from the stream yields sufficient sample for analysis. The method has the advantage of obtaining equilibrium data at constant pressure and temperature, but cannot be used at higher pressures where the effect of the so-called "inert" gas on the equilibrium becomes significant.

Dynamic Methods, Steady State. The superiority of the dynamic methods over the static ones becomes pronounced with the development of the steady-state methods.

In this case a dynamic equilibrium or steady state is established in which all variables such as temperature, pressure, and composition remain constant with time.

Rosanoff and co-workers (50) developed a method and apparatus depending on the fact that a constant-composition vapor bubbling through a liquid does not change in composition when the liquid is in equilibrium therewith. They continuously added the more volatile liquid to a still in amounts to keep its boiling point constant. Vapors bubbled through an "equilibrium chamber," and consecutive samples were assumed not to change.

The advantages of the above rather complicated procedure were maintained while the disadvantages were removed by automatically maintaining the still composition constant, by simply returning the condensate thereto. Thus, only a simple still, condenser, and trap is involved. The condensate is held up in a trap to allow for a sample for analysis. When the temperature of boiling is constant, the composition of the condensate reaches a constant value, which is the composition of the equilibrium vapor leaving the still. These conditions assure the attainment of steady-state conditions, after which samples of boiling liquid and vapor (after condensing and hold-up in the trap) are taken. Condensate in the trap is then recirculated back to the still to compensate for its previous removal and accompanying change in composition in the still. The use of a hold-up trap comes from Sameshima (51) and Yamaguchi (58). The original units were rather cumbersome and were designed to work at constant temperature.

A more simple recirculating still to determine data adequate for engineering design of distillation processes which operate at constant pressures was developed by Othmer (19,26,27,31,32), and has been widely used. The various models have undergone many refinements and improvements by many other investigators to simplify the use and to incorporate as nearly automatically as possible the principles involved, and thus secure a precision to the degree necessary for engineering use. It utilizes a boiling chamber with ample disengaging volume and surface so that the small droplets of vapor formed in the natural boiling operation may come to complete equilibrium automatically and without the necessity of other devices designed to improve such condition. The low velocities also minimize entrainment of liquid that may come from vapors disengaging from liquids at high velocities and which cause the vapor composition to be too low in more volatile constituents. Such equilibrium conditions will be unaffected by changes in rate of operation over the wide range that may be used. Furthermore, the discharge tube from the still is surrounded by vapors to minimize heat losses from this tube that might otherwise cause rectification to take place, and resulting vapor composition that is too high in more volatile constituents. For precise work, mention has been made (19,26,27) of the desirability of further heat insulation or supply to the still and its neck to prevent any small heat losses which might still prevail. When temperatures of vapors are to be secured, it is, of course, necessary to prevent influx of heat into the vapors and the thermometer to give a temperature reading that is too high. One of the later forms (26) of this still is drawn to scale in Figure 18. It employs the improvements of interchangeable glassware and is entirely automatic with simple supply of heat and cooling.

The desirability of the recirculation technique is shown in other methods and equipment of recent years. Thus, Nelson (25) employed a Cottrell pump in the boiler and an additional equilibrium chamber besides the boiler. Chilton (6) simplified the Nelson still by omitting the Cottrell boiler; however, Scatchard, Raymond, and Gil-

mann (52) used a short Cottrell boiler in a second chamber, designed to improve the approach to equilibrium. Gillespie (14) also used a Cottrell boiler as shown in Figure 19 in the unit external from the residue chamber (as was Nelson's); and the objections noted below are thus particularly emphasized.

However, the Cottrell boiler, which was originally developed for and used with pure substances (9) rather than mixtures, introduces more complication than improvement, since the rate of boiling has an undue effect upon the dynamic approach to equilibrium reached (12,26). Obviously a Cottrell pump should be used only if the

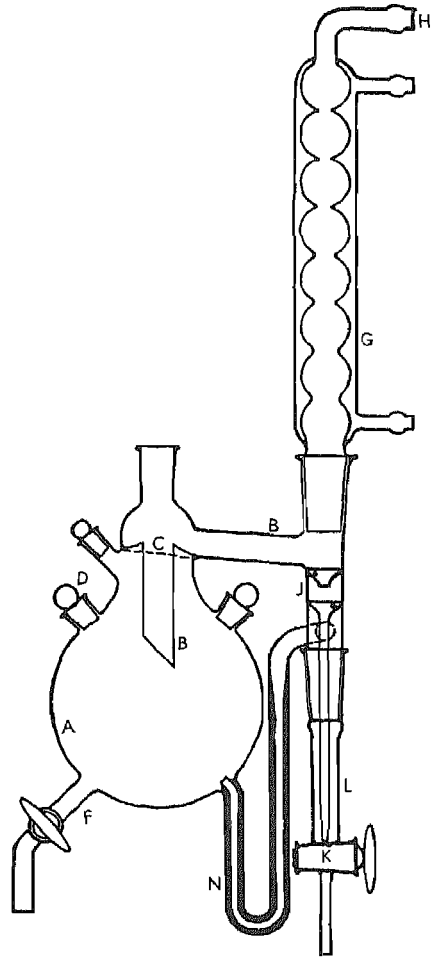


Fig. 18. Vapor-liquid equilibrium still (26). *A*, 800-ml. Kjeldahl flask or 4.5-in. (approx.) diameter balloon; *B*, central vapor outlet tube; *C*, vapor neck and sloped gutter for draining to receiver; *D*, openings for connections for electrical internal heater; *F*, liquid sample cock; *G*, condenser shell approx. 8.5 x 1.25 in.; balls 1 in. diam., constrictions varying from maximum opening at bottom to 0.25 in. at top; *H*, outlet to atmosphere or vacuum; *J*, drop counter as close to vapor inlet as possible with $\frac{3}{16}$-in. outlet, a $\frac{1}{16}$-in. hole vents receiver; *K*, bottom of receiver funnel not more than $\frac{1}{8}$ in. from stopcock (this funnel may be loose; or it may be inscaled just below drop counter; if inscaled, a $\frac{1}{16}$-in. vent hole is provided near top); *L*, interchangeable receivers for samples of different volumes, length to cock is 4 in.: *N*, heavy-walled tubing connecting overflow to still; this connection may be made on the back side as shown in dotted circle. This permits a cooling jacket to be used if a greater distance from the reservoir is allowed than shown. Return trap may be shorter if not water-jacketed, and connected at left just below drop counter and above top of reservoir joint.

This figure is $\frac{1}{4}$ scale.

vapors boiling from the liquid in the normal way are not in equilibrium with the liquid there (although no one has attempted to disprove the plausible assumption that equilibrium is reached with normal boiling). If vapor and liquid are not in equilibrium this results in their interchange between the liquid and vapor after leaving the boiler; and the equilibrium liquid leaving the vapor at the disengagement chamber of the Cottrell pump is not of the same composition as that in the pot, because its composition has been changed in the Cottrell pump. The vapor also is of different composition than would be in equilibrium with the boiling liquid from which the sample is taken.

Furthermore, heat losses in the system above the boiler (which is often uninsulated) will result in a slight condensation of vapors with a resulting change of composition in both phases. The extent of both effects is directly dependent upon the recirculation rate which will vary widely with change in heat supply.

A modification of the recirculating type of still with hold-up trap using a flash boiler was developed by Jones, Schoenborn, and Colburn (18), (see Fig. 20), to vaporize the condensate and pass vapors through the boiling liquid in an effort to improve the

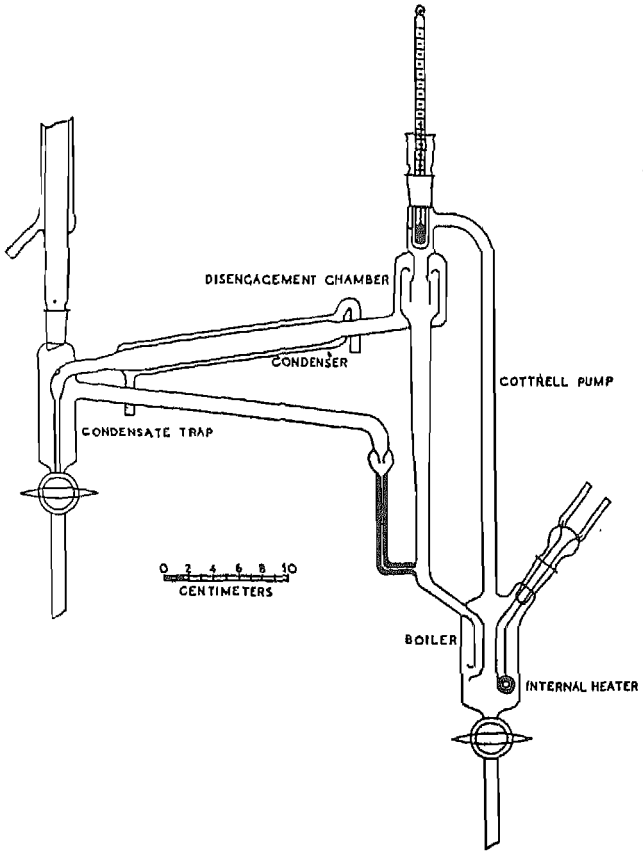


Fig. 19. Vapor-liquid equilibrium still using a Cottrell pump (14).

approach to equilibrium. Carney (4) and others have called attention to the careful control necessary of the temperature of the electrical resistance windings supplying heat losses from the boiler. If the heat supply is less than heat losses, condensation will occur and recirculation will stop; if greater there will be excessive vaporization and the flash boiler will be overloaded.

Another narrow range of operating conditions is in the heat supply to the flash boiler that must supply exactly the correct heat for complete vaporization. Otherwise there is necessarily a change in composition of vapor feed to boiler. If more heat is supplied and superheat results, or less and there is a vapor of different composition, the flask is called upon to act as a bubble tray of 100% efficiency, since the requirement is to establish equilibrium between vapor and liquid. Because of the high

vapor velocity, it is questionable whether this can be attained; and in general distillation practice a still pot is usually regarded as much more nearly an "equilibrium unit" than is a bubble tray. Entrainment is another possible error because of the high velocity.

The Cottrell boiler, the flash boiler, and the auxiliary contactor, while seemingly presenting desirable additions, add greatly to the complications of the unit and its operation. They have theoretical as well as practical disadvantages and require very careful control of rates of boiling and balance of multiple heat supplies. Variations in rate will possibly cause variations in the approach to equilibrium. In the case of the Cottrell boiler, the equilibrium temperature is especially sensitive to this rate, whereas, in the flash boiler, the composition of either the liquid phase or of the vapor phase may be unduly affected.

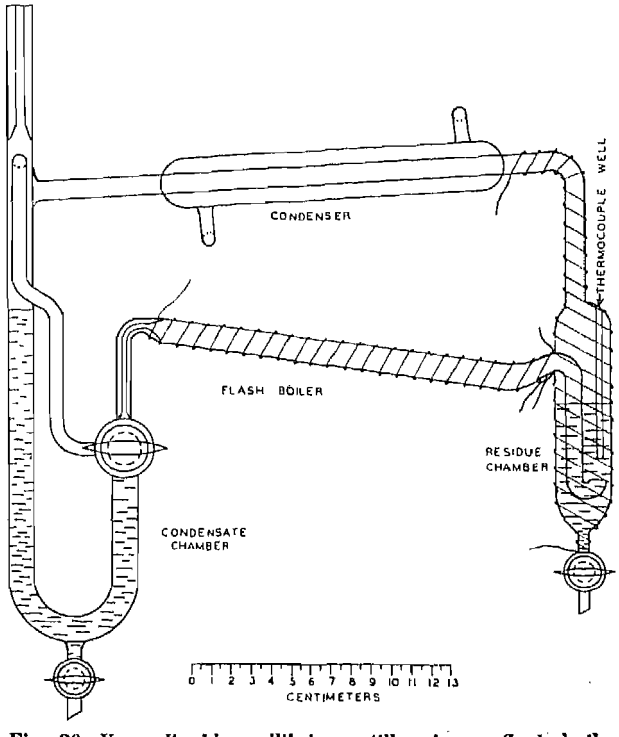


Fig. 20. Vapor-liquid equilibrium still using a flash boiler between receiver and main boiler (18).

Special Methods. Most of the specialized methods are based upon the recirculating still. However, one particular method might deserve more recognition. Carveth (5) as far back as 1899 described a method depending upon the measurement of temperatures only. A known mixture of the system is brought to a boil and its boiling point measured at a steady state. Then the dew point of the equilibrium vapor is determined, permitting the vapors to condense into a small hold-up tray; and the condensing temperature is measured. From these data, the vapor-liquid equilibrium curve of a binary may be determined. The original apparatus of Carveth was rather sensitive to boiling rate; there might be a possibility of developing the method to a greater precision, although results so far have not checked other methods.

Othmer, Ten Eyck, and Tolin (45) have applied the recirculating still to the determination of flash equilibrium data so necessary in petroleum refinery design by means of the apparatus shown in Figure 21. This gives data previously requiring a virtual

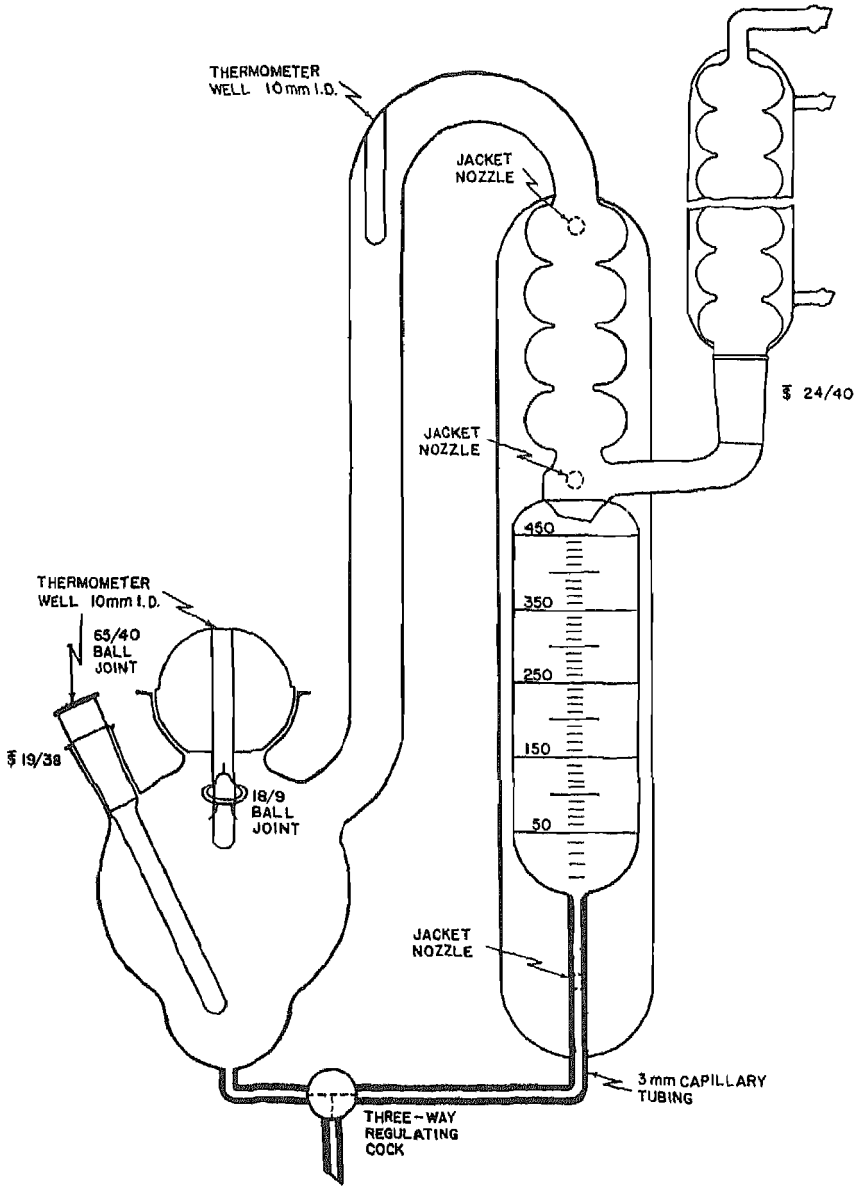


Fig. 21. Equilibrium flash vaporization still (45,55).

pilot plant for operations at every different percentage vaporized (as in a pipe still) of petroleum crudes or fractions under vacuum or atmospheric operation. The recirculating equilibrium still principle is utilized with a variable capacity in the receiver, so that from 10 to 90% of the original charge may be held up as condensate. Thus,

after a steady state is reached, the remaining liquid vaporizing in the pot is effectually in equilibrium with vapors corresponding to any given percent vaporized as in the usual petroleum flash distillation in a tube still. Data so obtained for any one pres-

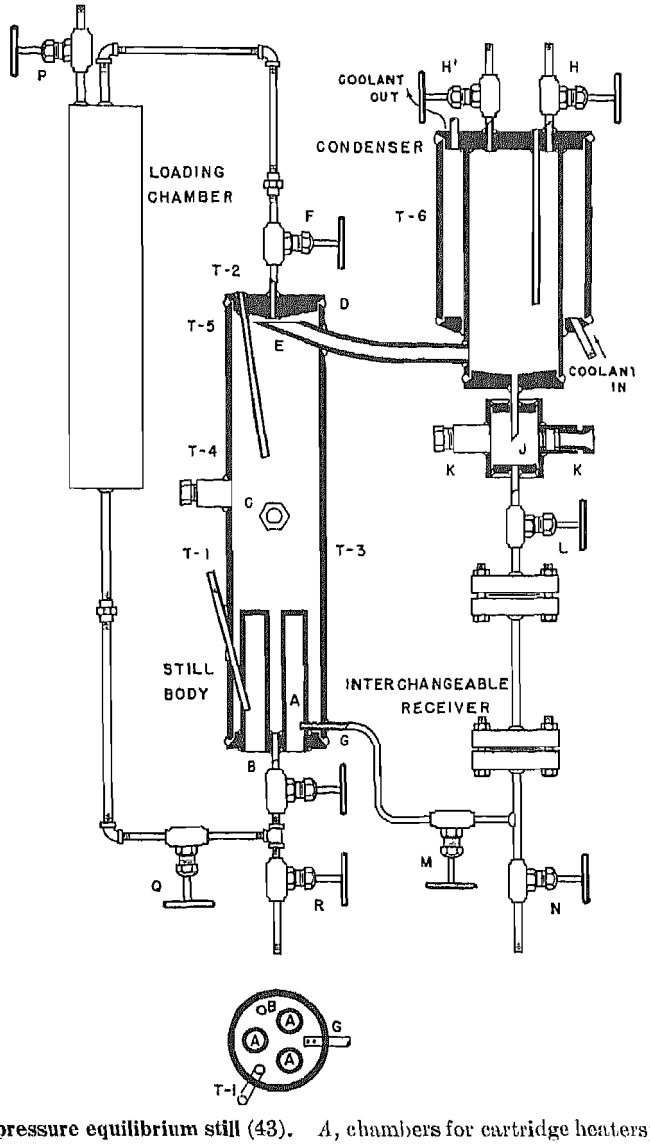


Fig. 22. High-pressure equilibrium still (43). *A*, chambers for cartridge heaters; *B*, liquid sample outlet with needle valve; *C*, peep sights, 90° apart and 1 in. difference in levels; *D*, cone-shaped top plate for allowing condensate to drain into vapor neck; *E*, vapor outlet pipe; *F*, vent valve for noncondensable gases; *G*, inlet tube for return of condensate, blanked at end, with four ⅛-in. holes to distribute liquid; *H*, valve to pressure-measuring system; *H'*, vent valve for noncondensables; *J*, condensate drop counter; *K*, peep sights; *L* and *M*, valves to isolate interchangeable condensate receivers; *N*, condensate sampling needle valve; *P*, valve for venting noncondensables and evacuating loading chamber; *Q*, valve for charging still body from loading chamber; *R*, valve through which loading is accomplished and liquid sample withdrawn. Thermocouples: T-1 for boiling liquid, T-2 for equilibrium vapors, T-3, T-4, T-5, thermocouples soldered onto outside of still body; T-6 on condenser.

sure may be converted for use at any other pressure or vacuum (55) in place of data requiring determination of vapors and liquid compositions, as indicated above (see p. 635).

The recirculating still has also been used for high-vacuum conditions by Perry and Fugitt (47) and others, and for high-pressure conditions up to 125 p.s.i. in a still made of standard Pyrex glass tubing with metal flanges (24) and for pressures up to 500 p.s.i. in welded stainless steel equipment (34,43) shown in Figure 22. In these cases the desired pressure was built up in a closed system by balancing the heat input to the boiler against the heat loss from the condenser.

Stills for Heterogeneous Azeotropes. One of the difficulties of the hold-up type of recirculating stills arises with the use of systems whose condensates separate into two liquid phases (8). In this case, the two phases must be returned to the boiler in the proper proportions in order to maintain a steady equilibrium state. One method of obviating this difficulty is to agitate the condensate with a stirrer in the hold-up trap so as to maintain uniform composition (23).

Bibliography

(1) Åkerlöf, G., and Teare, J. W., *J. Am. Chem. Soc.*, **62**, 620 (1940).
(2) Brown, F. D., *Trans. Chem. Soc.*, **35**, 547 (1879); **39**, 304 (1881).
(3) Carlson, H. C., and Colburn, A. P., *Ind. Eng. Chem.*, **34**, 581 (1942).
(4) Carney, T. P., *Laboratory Fractional Distillation*, Macmillan, N.Y., 1949.
(5) Carveth, J., *Phys. Chem.*, **3**, 193 (1899).
(6) Chilton, T. H., *Proc. Fourth Symposium, Chem. Eng. Educ.*, **64** (1935).
(7) Chu, J. C., *Distillation Equilibrium Data*, Reinhold, N.Y., 1950.
(8) Colburn, A. P., Schoenborn, E. M., and Shilling, D., *Ind. Eng. Chem.*, **35**, 1250 (1943).
(9) Cottrell, F. G., *J. Am. Chem. Soc.*, **41**, 721 (1919).
(10) Cox, E. R., *Ind. Eng. Chem.*, **15**, 592 (1923).
(11) Edwards, B. S., Hashmall, F., Gilmont, R., and Othmer, D. F., *Ind. Eng. Chem.*, **46**, 194 (1954).
(12) Ellis, A. M. R., *Trans. Inst. Chem. Engrs.*, **31**, 96 (1953).
(13) Fowler, R. T., *Ind. Chemist*, 718 (Nov. 1948).
(14) Gillespie, D. T. C., *Ind. Eng. Chem., Anal. Ed.*, **18**, 575 (1946).
(15) Gilmont, R., Roszkowski, T., and Othmer, D. F., *Petroleum Refiner*, **32**, No. 5, 167 (1953).
(16) Gilmont, R., Weinman, E. A., Kramer, F., Miller, E., Hashmall, F., and Othmer, D. F., *Ind. Eng. Chem*, **42**, 120 (1950).
(17) Hirata, M., *Chem. Eng. (Japan)*, **13**, 138 (1949).
(18) Jones, C. A., Schoenborn, E. M., and Colburn, A. P., *Ind. Eng. Chem.*, **35**, 666 (1943).
(19) Karr, A. E., Scheibel, E. G., Bowes, W. M., and Othmer, D. F., *Ind. Eng. Chem.*, **43**, 961 (1951).
(20) Langmuir, I., *Phys. Rev.*, **2**, 331 (1913); **8**, 149 (1916); *J. Am. Chem. Soc.*, **38**, 2221 (1916); *Trans. Faraday Soc.*, **17**, 607, 621 (1921).
(21) Li, Y.-H., *J. Chinese Chem. Soc.*, **2**, 108 (1934).
(22) Linebarger, C. E., *J. Am. Chem. Soc.*, **17**, 615 (1895).
(23) Moeller, W. P., Ph.D. Thesis, Polytechnic Institute, Brooklyn, N.Y., 1947.
(24) Moeller, W. P., Englund, S. W., Tsui, T. K., and Othmer, D. F., *Ind. Eng. Chem.*, **43**, 707, 711 (1951).
(25) Nelson, O. A., *J. Am. Chem. Soc.*, **54**, 1390 (1932).
(26) Othmer, D. F., *Anal. Chem.*, **20**, 763 (1948).
(27) Othmer, D. F., *Ind. Eng. Chem.*, **20**, 743 (1928).
(28) Othmer, D. F., *Ind. Eng. Chem.*, **21**, 576 (1929).
(29) Othmer, D. F., *Ind. Eng. Chem.*, **32**, 841 (1940).
(30) Othmer, D. F., *Ind. Eng. Chem.*, **34**, 1072 (1942).
(31) Othmer, D. F., *Ind. Eng. Chem.*, **35**, 614 (1943).
(32) Othmer, D. F., *Ind. Eng. Chem., Anal. Ed.*, **4**, 232 (1932).
(33) Othmer, D. F., and Benenati, R. F., *Ind. Eng. Chem.*, **37**, 299 (1945).
(34) Othmer, D. F., Chudgar, M. M., and Levy, S. L., *Ind. Eng. Chem.*, **44**, 1872 (1952).

(35) Othmer, D. F., and Gilmont, R., *Ind. Eng. Chem.*, **36**, 858 (1944).
(36) Othmer, D. F., and Gilmont, R., *Petroleum Refiner*, **30**, No. 11, 111 (1951); **31**, No. 1, 107 (1952).
(37) Othmer, D. F., and Josefowitz, S., *Ind. Eng. Chem.*, **40**, 723 (1948).
(38) Othmer, D. F., and Maurer, P. W., *Ind. Eng. Chem.* (to be published, 1955).
(39) Othmer, D. F., Ricciardi, L. G., and Thakar, M. S., *Ind. Eng. Chem.*, **45**, 1815 (1953).
(40) Othmer, D. F., and Sawyer, F. G., *Ind. Eng. Chem.*, **35**, 1269 (1943).
(41) Othmer, D. F., and Silvis, S. J., *Sugar*, **43**, No. 7, 28 (1948).
(42) Othmer, D. F., and Silvis, S. J., *Ind. Eng. Chem.*, **44**, 1872 (1952).
(43) Othmer, D. F., Silvis, S. J., and Spiel, A., *Ind. Eng. Chem.*, **44**, 1864 (1952).
(44) Othmer, D. F., and Ten Eyck, E. H., Jr., *Ind. Eng. Chem.*, **41**, 2897 (1949).
(45) Othmer, D. F., Ten Eyck, E. H., Jr., and Tolin, S., *Ind. Eng. Chem.*, **43**, 1607 (1951).
(46) Othmer, D. F., and White, R. E., *Ind. Eng. Chem.*, **34**, 952 (1942).
(47) Perry, E. S., and Fugitt, R. E., *Ind. Eng. Chem.*, **39**, 782 (1947).
(48) Perry, J. H., and Smith, E. R., *Ind. Eng. Chem.*, **25**, 195 (1933).
(49) Redlich, O., and Kister, A. T., *Ind. Eng. Chem.*, **40**, 341, 345 (1948).
(50) Rosanoff, M. A., *et al.*, *J. Am. Chem. Soc.*, **31**, 448 (1909); **36**, 1803 (1914); **37**, 301 (1915).
(51) Sameshima, J., *J. Am. Chem. Soc.*, **40**, 1482, 1503 (1918).
(52) Scatchard, G., Raymond, C. L., and Gilmann, H. H., *J. Am. Chem. Soc.*, **60**, 1275 (1938).
(53) Scatchard, G., *Trans. Faraday Society*, **33**, 160 (1937).
(54) Scheibel, E. G., *Ind. Eng. Chem.*, **41**, 1076 (1949).
(55) Ten Eyck, E. H., Jr., and Othmer, D. F., *Petroleum Refiner*, **32**, No. 9, 229; No. 10, 151 (1953).
(56) White, R. R., *Trans. Am. Inst. Chem. Engrs.*, **41**, 539 (1949).
(57) Wohl, K., *Trans. Am. Inst. Chem. Engr.*, **42**, 215 (1946).
(58) Yamaguchi, Y., *J. Tokyo Chem. Soc.*, **34**, 691 (1913).
(59) Young, S., *Distillation Processes and Principles*, Macmillan, London, 1922.

DONALD F. OTHMER AND ROGER GILMONT

/APOR PRESSURE. See *Vapor–liquid equilibria.*

/ARIABILITY; VARIANCE; VARIATION. See *Quality control*, Vol. **11**, pp. 355, 369.

/ARNISHES

For the purposes of this article, a varnish is considered to be a transparent, homogeneous, heat-treated blend of drying oil, resin, drier, and solvent, which, when applied as a thin film, will, upon evaporation of the solvent, oxidize and/or polymerize to form a hard continuous transparent coating. Varnishes are used primarily to protect substrates under the following circumstances: (*1*) where the coated surface must remain visible, for example, coatings for wooden furniture, overprint varnishes for paper labels; (*2*) where the coated surface need not be obscured, and where a varnish will provide better protection or do so at lower cost than will a pigmented coating (enamel), for example, food-can coatings, insulating varnishes, bottle-cap liners.

Varnishes often are used to make aluminum coatings by the simple addition of aluminum lining or paste.

The term varnish is also used for the pigment-binding component of pigmented products such as interior wall paints and enamels. When varnishes are used in pigmented systems, the driers are usually omitted from the varnish along with a large portion of the solvent, and both are added to the completed batch. The varnish so used is called a paint vehicle and actually does not meet the requirements of a varnish as defined above. See *Coatings* (*industrial*); *Paint.*

The above definition of the term "varnish" agrees closely with the historical con-

cept of varnish composition and function. Varnish meant one type of product, the so-called oleoresinous (oil plus resin) varnish. Also, functionally, the product had to dry per se to form a clear film. However, through the years, the term has been broadened and perhaps misused to describe other products using similar raw materials or performing similar functions. Some of these products contain a resin only, others contain black, opaque resins; some will not dry alone, but are used to make pigmented coatings, to which the driers are later added. These products will be mentioned briefly for purposes of clearer differentiation from the true or "oleoresinous" varnishes, which are the subject of this article.

Products called varnishes but not meeting the requirements of the definition are: (*1*) spirit varnish, (*2*) alkyd resin varnish, (*3*) asphalt varnish, and (*4*) litho varnish.

(*1*) A **spirit varnish** is a solution of a resin, with very little or no oil, in a volatile solvent. The solution usually is made at room temperature, that is, the resin is *cold-cut* in the solvent. Spirit varnishes dry by evaporation only, and therefore can be made to dry very quickly by the use of a fast-evaporating solvent. However, since most resins are fairly brittle, the resultant coating exhibits poor flexibility. Therefore, spirit varnishes are used when speed of drying is important and flexibility is not.

Shellac (*q.v.*) is by far the most common spirit varnish in use at the present time. It is a solution of lac resin in denatured alcohol. The most important application of shellac as a coating is its use as a clear finish for wood furniture or floors. In this application it serves very well because of its unique combination of properties, which cannot be matched by other coatings without rather complicated formulation. These are its properties: mild odor, ease of application by brush, good color and color retention, good sealing qualities without darkening the wood, excellent clarity enhancing the beauty of the wood, satin finish (dewaxed shellac will produce a high-gloss finish), surface slip (because of its wax content), ease of rubbing or sanding, ease of maintenance since it is readily repaired, ease of removal by sanding, and good interior wearing qualities. However, when resistance to water or cleaning compounds or exterior durability are required, other varnishes are preferred.

(*2*) **An alkyd resin varnish** is a solution of an alkyd resin (*q.v.*) in a volatile solvent with driers added, and is similar to a varnish in that an oil-modified resin is dissolved in a volatile solvent. However, there is a very marked difference in raw materials used and in the method of manufacture. In a varnish, an oil and resin are essentially blended during the heat process. The chemical reaction between the two is of relatively minor importance for most resins. Even when resins are formed during the heat process (metallic resinates or rosin derivatives, see p. 647), the starting material usually is rosin, which is resinous in nature. However, when an alkyd resin is made, the raw materials for the resin are chemicals that combine to form an entirely new product (such as glyceryl phthalate), which is resinous in nature, but which is not made as a resin per se but always produced in chemical combination with the oil. Also, the drying oil is not used in that form, but as the fatty acid or monoglyceride to enable the oil to react with the resin portion during its formation.

Alkyd resin varnishes have properties that are similar to oleoresinous varnishes, and can be used to perform the same functions. See *Alkyd resins*; *Coatings* (*industrial*).

(*3*) An **asphalt varnish** is a solution of asphalt (natural or petroleum) in a volatile solvent. Since these resins are not too soluble, the solution is made at fairly high temperatures (300–500°F.). Asphalt varnishes are black in color, and therefore are used as black enamels in applications where their low cost or excellent chemical resistance are desired. See *Asphalt* (*uses*).

(*4*) A **litho varnish** usually is a linseed oil, which has been oxidized and polymerized to a fairly high viscosity (5–200 poises). It is blended with driers and/or resins and used as a vehicle for pigmented lithographic printing inks. See *Printing ink*.

History. The origin of the term varnish is obscure. However, the word appears to have been derived from the ancient name for amber. Amber, a natural resin and former varnish ingredient, was called "berenice" after the name of an ancient Greek Queen Berenice, wife of Ptolemy Eugertes, king of Egypt, about 250 B.C. Returning from an Egyptian conquest, the warriors brought back a gift of amber, which, since its color matched the queen's hair, they named Berenice in her honor. Hence the Latin word vernix and its later Italian form vernice, whence the English word "varnish." The name finally referred to the fluid compound of resin and oil rather than to the resin itself. The German name for amber is Bernstein or Berenice's stone.

Raw Materials

Four groups of raw materials are used in the manufacture of varnishes: resins, oils, volatile solvents, and driers.

RESINS

Resins, as used in varnishes, are hard, brittle, noncrystalline solids, most of which will melt and will dissolve in organic solvents. When melted or dissolved, and then applied in a thin layer, the resin will form a continuous film. Some of the harder natural resins, such as Congo, will neither melt nor dissolve in oils or solvents. However, after a "running" process, these resins will do so readily.

The principal functions of the resin, when used in a varnish, are to contribute drying speed, hardness, toughness, and gloss.

Natural Resins (see *Resins, natural*). Imported natural resins, such as Congo, Batu, East India, and dammar, no longer occupy the important position they once held in the protective coatings industry. They have been largely replaced by synthetic resins except for a few specialty applications.

Rosin is by far the most commonly used natural resin. It is not used alone, but is treated to form a large group of rosin derivatives and other modified synthetic resins. This reaction may take place during the varnish cook or the rosin may be pretreated and sold to varnish manufacturers as a synthetic resin. See *Rosin and rosin derivatives.*

Metallic Resinates. Rosin is treated with hydrated lime or with zinc oxide. The resultant calcium and zinc resinates (see Vol. **11,** pp. 800–2) are generally used where very low-cost resins are desired.

Ester Gum. The ester formed by neutralizing rosin with a polyhydric alcohol, such as glycerol or pentaerythritol is called ester gum (see Vol. **11,** p. 802). It has fairly good color retention at low cost.

Pure Phenolic Resins. Under certain conditions of manufacture the condensation polymer can be made oil-soluble. Pure phenolic resins are unique among varnish resins in that they will combine chemically with the drying oil *during the cook* and will continue to polymerize to form a very resistant, flexible, oil-modified resin. The resin is outstanding in its contribution to flexibility of the varnish, so that smaller percentages of oil are required to produce the desired flexibility, as compared with varnishes made with other resins.

Pure phenolic resins are used in the manufacture of high-quality varnishes, where outstanding chemical and water resistance or outstanding durability are desired. See *Phenolic resins.*

Modified Phenolic Resins. Pure phenolic condensation products can also be caused to react in the presence of rosin. The resultant product is then neutralized with a polyhydric alcohol to form a "modified phenolic." When used in varnishes, these resins produce good drying speed and very good resistance to water and mild chemicals. However, they do not have good color retention. Modified phenolic resins are among the most widely used varnish resins, where color retention is not of primary importance, because of their moderate cost and all around good properties.

Maleic resins produce fast dry and excellent color retention. Therefore, they are used in varnishes for pale furniture woods, where color retention is important. See Vol. 1, p. 525.

Terpene Resins (*q.v.*). Pure terpene resins are very pale in color and almost neutral in acidity. They compete with ester gum for the production of low-cost varnishes with fair color retention.

Mixed terpene-phenolic resins have characteristics between pure phenolic and pure terpene resins. They produce varnishes with durability equal to the pure phenolics, but with better color retention as a result of the terpene content.

Coumarone Indene Resins (*q.v.*). These have very low acidity and very good alkali resistance, but are poor in color retention. They are used principally in aluminum paints, because of their nonactivity and good package stability. They are also used in low-cost alkali resistant varnishes such as concrete curing compounds to inhibit water evaporation from freshly placed concrete.

Petroleum Resins. These are polymers of unsaturated hydrocarbons obtained in the cracking of petroleum oils. They are low in cost and compete with ester gum and pure terpene resins in the production of low-cost varnishes with fair color retention.

Epoxy Resins. Considering the original definition of a varnish as described in this article, the epoxy resins and esters are not true varnish resins. They actually are in a class by themselves being closest to the alkyd resins in general characteristics. However, they serve to show the modern changes in varnish technology, and how the industry has been forced to broaden its original concept of a varnish because of the new raw materials from which varnish-type coatings are being made.

Epoxy resins are condensation products of epichlorohydrin and "bisphenol," $(CH_3)_2C(C_6H_4OH)_2$ (see Vol. **10,** pp. 307, 317, 359). Therefore they act as phenolic resins, but have a hydroxyl group that will react with a fatty acid to form an ester similar to an alkyd. Since they are resinous in nature, epoxys may be dissolved in solvents and used as resin solutions exhibiting excellent flexibility even without added plasticizer. Moreover, because of the reactive group, coatings made with them can be cured at room temperature by the use of an amine, resulting in coatings that will equal baked coatings in performance. Also, the resin solutions may be combined with urea or melamine to form excellent baked coatings.

Whether used as solutions or as esters, epoxy resins will produce coatings with excellent adhesion and flexibility and with good color and color retention. In the solution form, the epoxy resins exhibit excellent chemical and abrasion resistance. However, they must be dissolved in expensive lacquer solvents and because of the high cost of the finished product are used for specialty coatings only.

On the other hand, the epoxy esters are soluble in petroleum solvents and are much lower in cost approaching the cost of high-grade alkyds and phenolic varnishes. In fact they act somewhat like a mixture of the two exhibiting the chemical resistance of the phenolic varnish and the adhesion, flexibility, and color retention of the alkyd.

OILS

Oils give the varnish its flexibility, adhesion, and durability. They vary considerably in speed of polymerization and oxidation as shown below. Oils may be used in the natural form (after refining to remove mucilaginous materials), but may also be physically or chemically treated to improve viscosity, drying speed and resistance to water and chemicals.

Natural Oils (see *Drying oils*). Of the natural oils the most reactive are tung

(Chinawood), oiticica, linseed, safflower, and fish (menhaden or sardine). Soybean oil is one of the least reactive.

Tall Oil (*q.v.*). Another oil of increasing importance is tall oil, which actually is a blend of oil and rosin acids recovered from the black liquor in the manufacture of pulp by the sulfate process. Tall oil may be upgraded by redistillation whereby the oil (fatty) and rosin acids are separated. Tall oil can be esterified during the varnish cook to produce an oil-ester gum blend, or the redistilled fatty acids can be esterified in a similar manner to produce an oil similar to soybean.

Polymerized (Heat-Bodied) Oils. The main purpose of the heat processing of varnishes is to polymerize the oil in the presence of the resin. The resin itself contributes little to the process and may actually slow up the reaction.

In fast-bodying oils such as tung oil, polymerization is so rapid (5–10 min.) at the high temperatures normally reached (560–80°F.) that resins are added, since they tend to slow up this reaction. However, with the slow oils such as linseed and fish, the time required to polymerize the oil to the desired viscosity in the presence of the resin is too long for practical production (6–8 hr.), and, the resin in contact with the oil for such a long period would cause considerable darkening of the finished varnish. The slower oils are therefore heated alone at the optimum temperatures for polymerization (550–600°F.). Under these conditions a fairly high intermediate viscosity (5–200 poises) can be obtained, with little adverse effect on color. These polymerized oils can then be processed with the resins, completing the polymerization in a much shorter time and with much better color for the final product.

Treated Oils. Varnish oils may be upgraded to improve their drying speed, and to reduce or eliminate the time required for polymerization. In effect, the treatment improves the reactivity of the oil. The various methods of treatment used are: solvent segregation, oil splitting and reesterification with alcohols other than glycerol, isomerization, dehydration, maleinization, copolymerization, catalysis. See *Drying oils*. Important varnish products made by these processes include fish oil treated by solvent segregation or by oil splitting and reesterification, isomerized linseed or soybean oils, dehydrated castor oil, maleinized linseed or soybean oils, fish oil copolymerized with cyclopentadiene, linseed or soybean oils copolymerized with styrene, and linseed oil treated by catalysis.

VOLATILE SOLVENTS

Solvents (*q.v.*) are used principally to reduce the viscosity of the polymerized oil plus resin base so that it may be applied in a thin film. After application of the varnish, the solvent evaporates leaving the film completely. The more common solvents are listed in Table I in order of their speed of evaporation. The faster solvents are used where fast dry is desired and the varnish can be sprayed, for example in furniture finishing. The slower solvents are used when time must be allowed for proper application, for example in brushing varnishes. The solvents are listed also in low and high solvent power classifications. The high-powered solvents will dissolve certain synthetic resins, which are insoluble in the more commonly used low-powered solvents. Also, when so desired, they will dissolve the oil-resin base more efficiently, producing a finished varnish of lower viscosity at equal concentration.

TABLE I. Varnish Solvents.

Low solvent power		High solvent power	
Aliphatic from petroleum	Kauri butanol value[a]	Aromatic from petroleum or coal tar	Kauri butanol value[a]
V.M. & P. naphtha[b]	35–40		
Toluene substitute[c,d]	35–40	Toluene	100
Xylene substitute[d]	35–40	Xylene	95
Mineral spirits			
Standard	35–40	High-flash naphtha	85
Odorless	25		
High-strength[e]	60–80		
Refined kerosene	30–35		

[a] The higher figure denotes a stronger solvent.
[b] See Vol. **10**, p. 167.
[c] Solvents arranged in order of their speed of evaporation: toluene substitute is fastest, refined kerosene slowest.
[d] These have the same evaporation, but much lower solvent strength than the corresponding aromatic solvents.
[e] A blend of aromatic and aliphatic mineral spirits produced from high aromatic crudes or by catalytic hydrogenation.

DRIERS

Except when the oil content is very low, varnishes require catalysts or so-called driers to accelerate the oxidation and polymerization process of the applied film. Driers are soaps of the heavy metals, usually lead, cobalt, or manganese. The drier may be made during the cooking process by adding the metallic salt or oxide to the batch at temperatures ranging from 450–550°F. The salt or oxide reacts with the free acid in the oil and/or resin to form the drier. The more common procedure is to add a previously prepared drier solution to the finished batch. The driers most used in order of decreasing importance are: naphthenates, tallates, ethylhexoates (octoates), linoleates, and resinates. See *Driers and metallic soaps.*

Oil Length

The oils and resins used in a varnish are blended in varying proportions depending on the hardness (from the resin) or flexibility (from the oil) desired. The ratio of oil to resin is expressed as gallons of oil per 100 lb. of resin, and is called the "oil length" of the varnish. Varnishes usually are classified as to oil length as well as to the major types of oil and resin used in their manufacture. The more common varnishes can be grouped as follows:

Short (5–15 gal. oil length). A typical example is a furniture finish in which fast dry, hardness, and sanding qualities are more important than flexibility.

Medium (15–30 gal.). Floor varnishes are good examples of this type. Here hardness plus some flexibility (toughness) are important. The low-medium oil-length varnishes (15–25 gal.) are used for indoor finishes and the high-medium oil-length varnishes (25–30 gal.) are used for exterior floor coatings.

Long (35–50 gal.). Exterior varnishes are the most typical of this group. These coatings must withstand sunlight, which tends to embrittle the film, and temperature changes, which affect the dimensional stability of the substrate. In this case the flexibility of the varnish is much more important than its hardness. The resin component is used principally to improve drying speed and resistance to water and salt atmospheres. A few resins, however, for example, the pure phenolics, con-

tribute to the flexibility of the oil. In this case shorter oil lengths (25–35 gal.) may be used with excellent results. (Exterior varnishes are commonly called spar varnishes. This name dates back to the days of the sailing ships, when the many spars and masts on these ships were varnished. Obviously, this coating had to be of high quality to withstand sun and sea. Today, the name still denotes an exterior varnish of superior quality.)

Extra Long (60–200 gal.). Extra long varnishes, which actually are fortified oils, are used in special applications where extreme flexibility is required. This is important in applications such as cable coverings where the substrate or protected product is to be bent or flexed in service.

Manufacture

Heating the varnish components (cooking) performs one or several widely different functions: polymerization, depolymerization, melting and accelerated solution, formation of metallic soaps, esterification, gasproofing, and distillation or evaporation. The art and science of varnish cooking depend entirely on the control of these separate functions.

Polymerization. See p. 649.

Depolymerization. Some natural resins, for example, Congo or kauri, are so high in molecular weight that they are insoluble in drying oils. By heating the resin to 600–650°F., the resin structure breaks down, releasing volatile constituents with a consequent loss of 10–30% of the original resin. The remaining resin is quite soluble in oil, and can then be further processed to form a finished varnish. This procedure is called *gum running* and the run resin is called a *slack-melt* resin if partially soluble or a *fine-melt* resin if completely soluble in the oil.

Melting and Accelerated Solution. The temperatures reached during varnish processing are high enough so that the viscous or solid ingredients become fluid and blend readily. Likewise, at elevated temperatures incorporation of the solvent into the cook is far less difficult and time-consuming than would be the case if the solvents were added at room temperature.

Formation of Metallic Soaps. Two types of metallic soaps, metallic resins and metallic driers, may be made in the varnish kettle.

Metallic Resins. As stated under resins, rosin is an organic acid, which must be neutralized with certain metals or alcohols to form usable varnish resins. The most common metal plus rosin combinations are calcium and zinc resinates, which can be purchased as hard resins, or can be made in the kettle by reaction of rosin with the oxide or hydroxide at 450–550°F. In general, the calcium resinate (called limed rosin) usually is made in the kettle. On the other hand, because of the difficulty of manufacture, the zinc resinate usually is purchased as a resin or in a concentrated solution in mineral spirits.

Metallic Driers. See p. 650.

Esterification. To the varnish maker esterification means the process of treating rosin or tall oil with a polyhydric alcohol to form an ester. Glycerol and pentaerythritol are typical of the alcohols commonly used. The reaction temperatures are in the range of 450–525°F.

Gasproofing. The very reactive conjugated oils such as tung, oiticica, or dehydrated castor oils have a tendency to "frost," that is, to dry to partially crystallized

films. This effect is accelerated if the varnish is dried in an oven which is fouled with products of combustion from the heating unit. The dried film may also exhibit a slight checking or a "crows foot" wrinkle formation. Therefore the term "gas checking" is commonly used to describe this phenomenon. This undesirable film formation may be eliminated by heating the oil to fairly high temperatures, that is, 450–580°F. depending on the oil and the type of resin with which it is being processed. It is believed that at these temperatures some of the conjugated bonds of the oil are shifted to an isomeric and nonconjugated position thus eliminating extreme reactivity during oxidation, but without markedly affecting the rate of polymerization. This oil treatment is called gasproofing.

The tendency to gas check is used to advantage in the preparation of "wrinkle" finishes. To produce finishes of this type, the varnish is purposely cooked at relatively low temperatures to increase viscosity without gasproofing the oil.

Distillation or Evaporation. Distillation is used to remove undesirable products from the varnish during processing. Examples of such products are the volatile constituents of run natural resins, excess glycerol left after reaction with rosin or tall oil, or water produced by esterification. These products may either be condensed and recovered, or removed with the other varnish fumes.

EQUIPMENT

The equipment used in processing varnishes is of two general types, both of which are in common use: open portable kettles on open fires, and closed stationary kettles with self-contained heat sources (see *Furnaces*, Vol. 7, p. 36).

Portable Kettles. The older equipment consists of an open flat-bottomed cylinder (kettle) resting on a 3- or 4-wheel truck and heated over an open fire located within a "varnish" stack to remove the fumes. The height and diameter of the kettles may vary from 36 to 48 in. with a gross volume varying from 150 to 370 gal. The kettles may be made of steel, copper, Monel, aluminum, or stainless steel.

The kettle is loaded in the loading room, then placed over the fire pit. During the heating process the batch may be stirred, by hand, or by an agitator. When the heat processing is completed, the kettle is removed to another stack for cooling. When the correct temperature for solvent addition is reached (300–450°F.), the kettle is removed to a third location, the thinning room, where the solvent and drier solutions are added.

Stationary Kettles. Modern equipment consists of a totally enclosed autoclave set over or within a totally enclosed source of heat. The autoclave is a vertical cylinder with dome-shaped top and bottom. Usually, it is made of stainless steel. The unit is equipped with permanently connected accessory devices such as an agitator and thermometer or pyrometer, with an automatic control of the heat source, inert gas inlet, condenser, and a cooling device for fast reduction of temperature. Gross volumes vary from 500 to 8000 gal. Heating may be by gas or oil fires directly beneath the autoclave, by electric heaters in direct contact with the shell, or by circulating Dowtherm or hot oil in a jacket surrounding the unit.

Liquid raw materials are pumped directly into the kettle. Solid raw materials are added through a loading manhole, which can be locked into place. During the operation the autoclave is completely enclosed, thus minimizing fire hazards. Processing may be done under an inert gas atmosphere or a small amount of the volatile solvent may be introduced to form an azeotrope (a constant-boiling mixture) (solvent

process). The temperature is automatically adjusted, thus insuring much better quality control than is possible with the open kettles.

The completed batch is cooled by the auxiliary cooling system, and is then pumped into an agitated reducing tank which is equipped with its own condenser to prevent loss of solvent.

Modifications of both types of units are used to a limited extent. For example, stationary open kettles are used to polymerize large batches of oil. On the other hand, some portable kettles varying from 200 to 750 gal. in capacity have tightly fitting covers completely equipped with agitator, gas inlet, and condenser. These kettles duplicate the large stationary units to some degree and have the added advantage of lower initial cost.

Hazards

By far the most important danger in varnish processing is that of fire. Typical causes of varnish fires are: vapor flash from oil or solvent, autoignition, and foam. Although these hazards exist to a slight degree in closed-kettle units, they are far more dangerous and more prevalent in the older open-kettle process.

Vapor Flash. Drying oils will flash and ignite if the temperature reached during the cook is excessive. Flashing temperatures vary with the oil (600–650°F.) but are rarely reached during normal processing. Fire usually occurs as a result of carelessness, allowing the kettle temperature to run too high.

Solvents flash at temperatures far below those at which they are added to the varnish. For example, mineral spirits will flash at 105°F., but is added to a varnish base at 400–450°F. Thus, the vapors that are produced during the thinning process will ignite readily if they should come in contact with an open fire or a red-hot kettle bottom or truck. For this reason, kettles are always cooled away from the open fires, and are thinned in a special thinning room located well away from the processing area.

Autoignition. Very reactive oils, particularly tung oil, are exothermic in reaction during polymerization. If polymerization takes place too rapidly, the temperature can easily go out of control and spontaneous combustion may occur.

Foam is caused by water changing to steam at temperatures above 212°F. Water may be present in the varnish raw materials or may be formed during a reaction such as esterification or metallic soap formation. This water may cause foaming at three stages during the process. (*1*) During the upheat, if water is present in the raw materials. (*2*) If a reaction, of which water is a by-product, occurs suddenly, the water coming off at the usual reaction temperatures (450–550°F.) will form steam and cause foaming. (*3*) When the batch of varnish has cooled to a temperature of 300–450°F. (depending on the volatility of the solvent to be added), the solvent is added to the batch. If any water is present in the solvent (which is at room or tank temperature) when the solvent is mixed with the hot batch, the water will suddenly turn to steam and cause foaming. However, this usually is not a fire hazard since the thinning room is always placed well away from the varnish fires.

Tests and Specifications

Some of the tests described below are used as quality control tests in production. Most of them are used by prospective consumers, either industrial or governmental,

to determine whether or not the varnish will perform the functions for which it has been designed.

PRODUCT TESTS

Color (A.S.T.M. D154–50, TT-P-141b-424.8). The paler the varnish, the less it will discolor the surface on which it is applied. Color is measured by means of an arbitrary system called the Gardner or Hellige color standards, which are rated from 1 to 18 in increasing depth of color. Pale varnishes have colors ranging from 7 to 10, and standard varnishes have colors ranging up to 14. Raw linseed oil for example has a color of 11.

Viscosity (A.S.T.M. D154-50, TT-P-141b-427.1). The application for which the varnish is intended determines its viscosity as shown in Table II. Viscosity is measured in absolute units (poises) or more often by an arbitrary set of standards called the Gardner-Holdt viscosity standards. Gardner-Holdt viscosities range from A to Z-10 in increasing viscosity.

TABLE II. Typical Viscosities.

Material	Viscosity	
	Gardner-Holdt	Poises
Floor sealers	Below A	Below 0.5
Raw linseed oil	A	0.5
Aluminum varnishes	A–D	0.5–1.0
Floor or spar varnishes	C–H	0.85–2.0
Tung oil	J	2.5
Paint vehicles	D–Z-6	1.0–200
Polymerized oils	Q-Z-6	4.4–200

Acid Number (A.S.T.M. D154–50, TT-P-141b-507.3). This is measured by dissolving a sample of varnish in a water miscible solvent mixture, for example alcohol and benzol, then neutralizing with a standard alkali solution in the presence of an indicator. The acid number is expressed as the number of milligrams of potassium hydroxide required to neutralize 1 gram of the sample.

In general, a low acid number (say below 15 based on the solids) is desirable since it denotes low residual reactivity in the varnish. A well-reacted varnish will have optimum drying qualities and water and chemical resistance for that particular type of varnish. Low acidity is especially important if the varnish is to be mixed with aluminum. An acid vehicle will cause loss of leafing of the aluminum in a comparatively short time.

Nonvolatile Content (A.S.T.M. D154–50, TT-P-141b-404.1). An important control test is the determination of the amount of solvent in the varnish. If the nonvolatile of a varnish is low (high solvent content) at the correct viscosity, then the batch has been overcooked, for example, overpolymerized. If the nonvolatile is high at a given viscosity the batch has been undercooked. Viscosity deviations within 1% of standard are considered acceptable, but a greater variation suggests future trouble, such as possible gelling during storage if the varnish is overcooked, and poor drying or poor water and chemical resistance if undercooked.

The nonvolatile content is determined by evaporating the solvent from a meas-

ured weight of the varnish by heating at 220°F., then calculating the percentage of base remaining.

Flash Point (A.S.T.M. D56–52, TT-P-141b-429.1). For optimum safety a varnish should have as high a flash point as possible consistent with desired drying qualities. (A fast-evaporating solvent will have a comparatively low flash point). For example, the Federal Government requirement is a minimum of 86°F. In many localities the minimum is 100°F. The Interstate Commerce Commission requires a red danger label on all products having a flash point below 80°F. Table III gives flash points of some varnish solvents.

TABLE III. Flash Points of Varnish Solvents (Tag Closed).

Solvent	Flash point, °F.
V.M. & P. naphtha	20
Mineral spirits	105
Toluene	40
Xylene	85
Hi-flash naphtha	105

Skinning (A.S.T.M. D154–50, TT-P-141b-414.1) is the tendency of the varnish to form an insoluble skin on its surface during storage. A well-processed varnish should not skin when stored in a full container. To check this property, a glass jar is filled ¾ full with the varnish and closed tightly. Some specifications require that no skin should be observed after 48 hours.

PERFORMANCE TESTS

Drying Speed (TT-P-141b-406.1). Fast drying is always desirable provided that other properties, such as brushing, are not adversely affected. Drying speed is of primary importance in varnishes for furniture and floors. In furniture varnishes, dust is always a problem, so drying must be extremely fast. Varnished floors must be reopened to traffic quickly, so again drying of the varnish should be as rapid as possible.

Drying is measured by flowing a thin film of the varnish on a flat panel of glass or smooth metal, then timing its "set to touch," "dry hard," and "dry tack free" characteristics. A varnish is set to touch when none can be removed by a light touch of the finger (usually the time when most of the solvent has evaporated). It is dry hard when it cannot be marred by finger pressure, and it is tack free when no stickiness or tack is felt under finger pressure.

Gas Checking (see "Gasproofing," p. 651) (TT-P-141b-416.1 or .2). Varnishes are tested for gas checking by allowing a coated panel to dry in a closed area such as a bell jar, in which a small gas flame is allowed to burn until it goes out due to lack of oxygen. A properly processed varnish will dry to a satisfactory film in this simulated foul atmosphere, but an improperly gasproofed varnish will check.

Flexibility (A.S.T.M. D154–50, TT-P-141b-415.1). Flexibility is of importance wherever a possibility exists that internal stresses of the substrate due to physical deflection or temperature changes may produce a break in the varnish film. This is especially significant in exterior or spar varnishes.

The test consists of mixing the varnish with increasing percentages of a brittle resin solution ("run" kauri in turpentine), then flowing out films of the mixtures on

tin panels and baking them in an oven for a number of hours. The panels are then cooled to room temperature and bent over a ⅛ inch mandrel. The percentages of added solution are increased until failure (cracking) occurs. The flexibility is recorded as the kauri reduction, that is, the maximum percentage (on weight of the nonvolatile of the sample) of added kauri solution at which the varnish passes the bending test. See Table IV.

TABLE IV. Flexibility of Varnishes.

Varnish	Kauri reduction, %
Furniture varnish	0–20
Floor varnish:	
Interior	20–50
Exterior	50–100
Spar varnish:	
Fair quality	50–80
Best quality	100–180

Water and Chemical Resistance (A.S.T.M. D154–50, D154–52T, TT-P-141b-601.1). All varnishes must have at least fair resistance to water and exterior or floor varnishes should have good water resistance. Water resistance is tested by partially immersing a well-dried coated panel in cold water (1 to 7 days) or boiling water (15 minutes to 7 hours), the time varying with the quality of the varnish. Some change in the panel after immersion is acceptable provided that the change is not noticeable after a short recovery period (1–2 hours). Immersion tests may also be run in other chemicals or solvents to which the varnish should be resistant. Caustic resistance is a common test for floor and factory maintenance varnishes. In this test a glass test tube is used inasmuch as the caustic will affect the tin panel. The concentration of the solution may vary from 1 to 5% NaOH and the time from 4 to 96 hours.

Color Retention. Varnishes differ widely in their tendency to discolor with age. However, varnishes for light surfaces such as bleached woods should have good color retention. There is no specific test for this property, but varnishes may be

TABLE V. Typical Varnish Specifications.

	TT-S-176a Floor sealer		TT-V-71d Floor and trim	TT-V-86 Cabinet rubbing	TT-V-121C Exterior spar
	Class 1	Class 2			
Color, max.	—	—	14	14	14
Viscosity, poises	0.5 max.	0.22 max.	0.85–2.0	1.25–2.0	0.85–2.0
Nonvolatile, minimum, %	40	25	45	45	55
Flash point, minimum, ° F.	86	86	86	—	86
Skinning, 48 hr.	None	None	None	None	None
Set to touch, hr.	1–3	1–3	½–2	½–2	½–2
Dry hard, max., hr.	7	7	7	7	8
Tack free, max., hr.	—	—	24	—	24
Gas checking	—	—	None	None	None
Flexibility (kauri), pass %	100	100	25	0	100
Water resistance					
Cold water, minimum, hr.	24	24	72	72	72
Boiling water, minimum, minutes	30	30	15	15	15

compared against each other, partly covered under normal daylight or under ultraviolet light for accelerated results. The superior varnish will show little or no change either in the exposed or in the covered area of the panel.

Durability (weathering) (A.S.T.M. D822–46T, D1006–51T, D1014–51, TT-P-141b-615.1 or 2, TT-P-141b-616.1). In the case of exterior varnishes, durability tests are the final measure of the protective value of the product. Panels of substrates similar to those to be used in practice are coated with the varnish and exposed in various ways. The most informative but the slowest method is to expose the panels under the identical conditions to which the product will later be subjected in practice. A faster method is to expose the panels at 45 degrees facing south in an area such as Florida with its comparatively high sunshine and rainfall. The fastest and least accurate method is to expose the panels in a weatherometer in which sunlight is simulated by carbon arc lamps and rainfall by an intermittent water spray. The weatherometer is useful as a screening test: A product that fails quickly in the instrument can usually be eliminated from further consideration. On the other hand, a product giving a good weatherometer result may still fail quickly under actual conditions of use..

Uses

The application of varnishes may be classified according to end use in the following groups:

Architectural coatings (buildings):
- (a) Interior floors (wood, linoleum, tile)
- (b) Interior trim (wood)
- (c) Exterior floors (wood)
- (d) Exterior walls (wood)
- (e) Mixing varnish for addition to paints to improve leveling, dry, and gloss.

Industrial coatings (manufactured objects):
- (f) Furniture (wood and metal)
- (g) Electrical insulation
- (h) Can linings
- (i) Metal roller coatings (Venetian blinds)

Marine varnishes:
- (j) Interior floor and trim (wood)
- (k) Exterior decks (wood)
- (l) Exterior superstructure (wood)

Printing:
- (m) Overprint varnishes for paper labels and lithographed metal

Specialty uses:
- (n) Chemically resistant varnishes for heavy industry
- (o) Alcohol-resistant varnishes for bar tops
- (p) Waterproofing for concrete floors and silos

Typical formulas

Typical formulas are presented below to demonstrate the processing and end uses of varnishes based on various oils and resins. The lead naphthenate contains 24% Pb as metal, cobalt naphthenate or linoleate 6% Co as metal, and the manganese naphthenate 6% Mn as metal. A general description of these formulations is given in Table VI.

TABLE VI. Typical Formulas.

Formula No.	Resin	Oil	Oil length	Process[a]	End use
1	Natural resin	Tung	8	Depolymerization	(f)
2	Ester gum	Oiticica, linseed	25	Gasproofing	(e)
3	Pure phenolic	Linseed	12.5	[a]	(g,h)
4	Pure phenolic	Tung	12.5	Gasproofing	(n,o,p)
5	Pure phenolic	Dehydrated castor, maleinized soybean	25	Gasproofing	(a,b,c,d, j,k,l)
6	Modified phenolic	Tung, linseed	9	[a]	(m)
7	Modified phenolic	Dehydrated castor	25	Gasproofing	(a,b,c,j,k)
8	Maleic	Tung, linseed	10	Gasproofing	(i)
9	Pure terpene	Dehydrated castor, tung	15	Gasproofing	(a,b)
10	Terpene phenolic	Tung	33	Gasproofing	(d,l)
11	Coal tar resin Pure phenolic	Tung	15	Gasproofing	(p)
12	Petroleum	Linseed, fractionated fish, tung	12	Gasproofing	(f)
13	Tall oil	Tall oil, dehydrated castor	20	Esterification	(b,c)

[a] In addition to listed processes, cooking serves to polymerize and accelerate melting and solution in each case.

FORMULA 1. Furniture Rubbing Varnish.

Constituent	Amount, lb.
Congo	130 (100 after running)
Tung oil	62
Mineral spirits	195
Lead naphthenate	1.0
Manganese naphthenate	0.2
Cobalt naphthenate	0.2
Total	*388.4*

Characteristics	
Oil length	8 gal.
Nonvolatile	45%
Viscosity	A–C
Dry tack free	2½ hr.
End use	f

Cooking procedure: Heat the Congo to 635–650°F. Hold the batch at this temperature until all the lumps go into solution. Allow the temperature to drop to 550°F. Then add tung oil and reheat to 560°F. Hold at that temperature until the desired viscosity is reached. Then remove the batch from the fire and cool rapidly by spraying water on the outside and bottom of the kettle. At 425°F. add the solvent and driers.

FORMULA 2. Mixing Varnish.

Constituent	Amount, lb.
Ester gum	240
Oiticica oil	425
Bodied linseed oil (Z)	55
Mineral spirits	450
Lead naphthenate	4
Manganese naphthenate	4
Cobalt naphthenate	4
Total	*1182*

(*Continued*)

FORMULA 2. Mixing Varnish (*Concluded*).

Characteristics	
Oil length	25 gal.
Nonvolatile	61 %
Viscosity	G-I
Color	13
Dry hard	8 hr.
End use	e

Cooking procedure: Heat the ester gum and oiticica oil to 570°F. in 50 min. Hold at that temperature for 8 min. Add the linseed oil. Allow the batch to cool to 450°F. Add the solvent and driers.

FORMULA 3. Can Coating.

Constituent	Amount, lb.
Bakelite 10282 (pure phenolic)	100
Admolene (catalyzed linseed)	97
Xylene	223
Lead naphthenate	2.0
Manganese naphthenate	0.3
Cobalt naphthenate	0.8
Total	*423.1*

Characteristics	
Oil length	12.5 gal.
Nonvolatile	47%
Color	12
Dry hard	8 hr. (air dry)
End uses	g,h

Cooking procedure: Heat the Admolene to 450°F. in 20 minutes. Remove the kettle from the fire, and allow the batch to cool to 440°F. Add the resin slowly while stirring constantly to avoid gelation. When all the resin is dispersed, heat the batch slowly to 360°F. Watch foaming. Hold for 45 min. Then remove from the fire and add the solvent and driers. This coating is baked at 212°F. for 1 hr.

FORMULA 4. Chemically Resistant Varnish.

Constituent	Amount, lb.
Bakelite 254 (pure phenolic)	100
Tung oil	100
Xylene	198
Lead naphthenate	0.2
Cobalt naphthenate	0.01
Total	*398.21*

Characteristics	
Oil length	12½ gal.
Nonvolatile	50%
Viscosity	D
Color	10
Dry hard	1 hr.
Dry tack free	4 hr.
Kauri reduction	0
5% NaOH for 96 hr.	O.K.
End uses	n,o,p

Cooking procedure: Heat resin and oil to 450°F. in 30 min. Hold at that temperature for 25 min. Allow the batch to cool to 300°F. Add xylene and driers.

FORMULA 5. Marine Spar Varnish.

Constituent	Amount, lb.
Bakelite 9400 (pure phenolic)	100
Castung 103 (G–H) (dehydrated castor)	160
Varsoy (Z-3) (maleinized soybean)	40
Mineral spirits	247
Lead naphthenate	8
Cobalt naphthenate	3
Total	*558*

Characteristics	
Oil length	25 gal.
Nonvolatile	55%
Viscosity	D
Color	12
Acid number	11
Set to touch	1 hr.
Dry hard	4 hr.
Dry tack free	8 hr.
Kauri reduction	140%
Boiling water (1 hr.)	O.K.
Cold water (72 hr.)	O.K.
End uses	a,b,c,d,j,k,l

Cooking procedure: Heat resin and oils to 585°F. Hold at that temperature for 10 min. Allow the batch to cool to 450°F. Add the solvent and driers.

FORMULA 6. Overprint Varnish.

Constituent	Amount, lb.
Krumbhaar 707 (modified phenolic)	100
Tung oil	40
Refined linseed oil	52.5
Cobalt linoleate	3
Cornstarch	1.5
Short-range kerosene	60
Total	*257.0*

Characteristics	
Oil length	9 gal.
Nonvolatile	75%
End use	m

Cooking procedure: Heat the resin, tung oil, and 40 lb. of linseed oil to 425°F. Hold at that temperature for a clear hard pill on glass. (The pill is produced by allowing a sample drop of the batch to cool on a glass panel. If the ingredients are completely dissolved the pill will be clear, and when the oil is sufficiently polymerized, the pill will be hard. At short oil lengths and especially where the concentration of tung oil is comparatively low, gasproofing is not a problem and it is unnecessary to cook at high temperatures.) Add 12.5 lb. of linseed oil and cornstarch. When these are completely dissolved, add the solvent.

FORMULA 7. Porch and Deck Varnish.

Constituent	Amount, lb.
Krumbhaar 505 (modified phenolic)	100
Castung 403(Z-3) (dehydrated castor)	200
Mineral spirits	245
Lead naphthenate	4.0
Cobalt naphthenate	1.6
Total	*550.6*

(*Continued*)

FORMULA 7. Porch and Deck Varnish (*Concluded*).

Characteristics	
Oil length	25 gal.
Nonvolatile	55%
Viscosity	H
Color	12
Acid number	5
Set to touch	1 hr. 20 min.
Dry tack free	5 hr.
Kauri reduction	100%
Boiling water (1 hr.)	O.K.
Cold water (72 hr.)	O.K.
End uses	a,b,c,j,k

Cooking procedure: Heat the resin and 100 lb. of oil to 585°F. Hold for a clear pill on glass. (High-melting resins and dehydrated castor oil are not readily miscible. This procedure ensures proper miscibility. The pill (cooled sample drop) determines initial miscibility before the process is continued.) Slowly add the balance of the oil, keeping the temperature above 500°F. Reheat the batch to 585°F. and hold at that temperature for 20 min. Cool the batch to 450°F. and add the solvent and driers.

FORMULA 8. Venetian Blind Varnish.

Constituent	Amount, lb.
Krumbhaar 414 (maleic resin)	100
Tung oil	64
Bodied linseed oil (Z)	16
Mineral spirits	180
Cobalt naphthenate	0.6
Total	*360.6*

Characteristics	
Oil length	10 gal.
Nonvolatile	50%
Viscosity	F
Color	8–9
End use	i

Cooking procedure: Heat the resin and tung oil to 565°F. Hold 5 min. Check with linseed oil. Cool to 450°F. Add solvent and drier.

FORMULA 9. Four-Hour Floor and Trim Varnish.

Constituent	Amount, lb.
Piccolyte S-115 (terpene)	100
Castung 403 (Z-3) (dehydrated castor)	80
Tung oil	40
Mineral spirits	220
Cobalt naphthenate	2
Lead naphthenate	5
Total	*447*

Characteristics	
Oil Length	15 gal.
Nonvolatile	50%
Viscosity	C
Color	10
Dry tack free	4 hr.
End uses	a,b

Cooking procedure: Heat the oils and resin to 580°F for 30 min. Hold at that temperature for 20 min. Allow the batch to cool to 440°F. Add solvent and driers.

FORMULA 10. Spar Varnish.

Constituent	Amount
Durez 500 (terpene phenolic)	100 lb.
Tung oil	33 gal.
Mineral spirits	37 gal.
Lead naphthenate	6.5 lb.
Cobalt naphthenate	2.6 lb.

Characteristics	
Oil length	33 gal.
Nonvolatil	60%
Viscosity	G–H
Color	12–13
Acid number	4.5
Set to touch	2 hr.
Dry tack free	6 hr.
Kauri reduction	140%
Boiling water (1 hr.)	O.K.
Cold water (72 hr.)	O.K.
End uses	d,l

Cooking procedure: Heat the resin and tung oil to 460°F. Hold at that temperature for 15 min. Remove the batch from the fire. Add the solvent and driers.

FORMULA 11. Concrete Sealer.

Constituent	Amount, lb.
Cumar V (coal tar resin)	70
Bakelite 254 (pure phenolic)	30
Tung oil	117
Mineral spirits	217
Cobalt naphthenate	1
Total	*435*

Characteristics	
Oil length	15 gal.
Nonvolatile	50%
Viscosity	K
Dry tack free	1¼ hr.
5% NaOH	Over 168 hr.
End use	P

Cooking procedure: Heat the oil and Bakelite to 500°F. Add the Cumar resin. Hold at 500°F. until the desired viscosity is reached. Allow the batch to cool to 425°F. Add the solvent and drier.

FORMULA 12.

Constituent	Amount, lb.
Piccopale 100 (petroleum resin)	100
Refined linseed oil	16
Hi-Frak (fractionated fish oil)	40
Tung oil	39
Mineral spirits	130
Lead naphthenate	2
Cobalt naphthenate	0.5
Total	*327.5*

(*Continued*)

FORMULA 12 (*Concluded*).

Characteristics	
Oil length	12 gal.
Nonvolatile	60%
Viscosity	F
Color	12
Dry tack free	6 hr.
End use	f

Cooking procedure: Heat the resin, Hi-Frak and tung oil to 525°F. in 30 min. Then heat the batch at a slower rate to 550°F. (10 min.). Hold at 550°F. for a hard pill on glass. Continue to hold at that temperature for another 20 min. Add the linseed oil. Allow the batch to cool to 425°F. Add the solvent and driers.

FORMULA 13. General-Purpose Utility Varnish.

Constituent	Amount, lb.
Tall oil	1000
Dehydrated castor oil (Z-3)	405
Pentaerythritol	136
Maleic anhydride	40
Mineral spirits	1530
Lead naphthenate	30
Cobalt naphthenate	10
Manganese naphthenate	5
Total	*3156*

Characteristics	
Oil length (equivalent)	20 gal.
Nonvolatile	50%
Viscosity	G
Acid number	8
Color	8
Dry hard	6 hr.
Kauri reduction	30%
End uses	b,e

Cooking procedure: A closed unit under carbon dioxide atmosphere is used. Charge the tall oil, dehydrated castor oil, and maleic anhydride into the kettle. Heat to 450°F. and hold for 30 minutes to form a maleic adduct. Slowly add the pentaerythritol with good agitation to prevent foaming. When all in, heat to 550°F. and commence sparging with carbon dioxide to remove water of esterification. Hold at 550°F. for 5 hours to viscosity. Allow to cool to 450°F. and add solvent and driers.

Bibliography

(1) A.S.T.M., *Standards on Paint, Varnish, Lacquer and Related Products.*

(2) Bidlack, V. C., and Fasig, E. W. (eds.), *Paint and Varnish Production Manual*, Wiley, N.Y., 1951.

(3) Federation of Paint and Varnish Production Clubs, *Standards and Methods of Test for Paint, Varnish, Lacquer and Related Products*, Federation of Paint and Varnish Production Clubs, Philadelphia, 1953.

(4) Gardner, H. A., and Sward, G. G., *Physical and Chemical Examination of Paints, Varnishes, Lacquers and Colors*, 11th ed., H. A. Gardner Laboratories, Bethesda, Md., 1950.

(5) Fischer, W. von, *Paint and Varnish Technology*, Reinhold, N.Y., 1948.

(6) Heckel, G. B., *Paint, Varnish and Lacquer Catechism*, 12th ed., Heckel, Philadelphia, 1952.

(7) Krumbhaar, W., *Coating and Ink Resins*, Reinhold, N.Y., 1947.

(8) Mattiello, J. J. (ed.), *Protective and Decorative Coatings*, Wiley, N. Y., Vols. I–V, 1941–46.

(9) New England Paint and Varnish Production Club, *Practical Paint Course*, American Paint Journal, St. Louis, Mo., 1954.

(10) *Official Digest, Federation of Paint & Varnish Production Clubs.*
(11) Payne, H. F., *Organic Coating Technology,* Wiley, N. Y., Vol. I, 1954.
(12) Radi, L. J., *Glossary for the Protective Coatings Industry,* 3rd ed., RBH Dispersions, Bound Brook, N.J., 1954.
(13) Singer, E., *Fundamentals of Paint, Varnish and Lacquer Technology,* American Paint Journal, St. Louis, Mo., 1954.
(14) Stewart, J. R., *The National Paint Dictionary,* 3rd ed., Stewart Research Labs., Wash. D.C., 1948.
(15) U.S. Dept. of Commerce, *Paint Manual,* Supt. of Documents, Wash. D.C., 1945.
(16) U.S. Dept. of the Interior, *Paint Manual,* Supt. of Documents, Wash. D.C., 1954.
(17) U.S. Federal Specifications: TT-P-141b, Paint, Varnish, Lacquer, And Related Materials; Methods Of Inspection, Sampling, And Testing (Jan. 15, 1949); TT-V-51a, Varnish, Asphalt (Feb. 2, 1944); TT-V-61, Varnish; Damar (April 20, 1939); TT-V-71d, Interior Varnish; Floor and Trim (Oct. 2, 1952); TT-V-81b, Varnish; Mixing for Aluminum Paint (Feb. 10, 1949); TT-V-86, Rubbing Varnish; Cabinet (June 29, 1939); TT-V-91b, Varnish; Shellac (July 18, 1950); TT-V-109, Varnish; Spar, Alkyd-Resin (April 10, 1950); TT-V-119, Varnish; Spar, Phenolic-Resin (July 27, 1950); TT-V-121c, Varnish; Spar, Water Resisting (Nov. 29, 1949).

SIDNEY B. LEVINSON

VASICINE, $C_{11}H_{12}N_2O$. See *Alkaloids,* Vol. **1,** p. 500.

VASOPRESSIN. See *Hormones (posterior-pituitary),* Vol. **7,** p. 492.

VAT DYES

Vat dyes are colored, water-insoluble organic compounds which possess the property of forming water-soluble alkali salts in an alkali reducing bath and whose solutions have affinity for cellulosic fibers. Regeneration of the insoluble dye from the water-soluble *leuco base* or vat form is accomplished by oxidation, usually with atmospheric oxygen. Vat dyes may also be applied to cellulose in the form of the alkali metal salts of their leuco sulfuric acid esters (Indigosols). (See Vol. **1,** p. 976; Vol. **5,** p. 398; Vol. **13,** p. 336.) The chief classes of vat dyes are the indigoid dyes (see Vol. **7,** p. 814), and the anthraquinone and related quinonoid dyes (see Vol. **1,** p. 966). Sulfur dyes (see Vol. **13,** p. 445) are also sometimes included. For pigments from vat dyes, see *Pigments (organic),* Vol. **10,** p. 673.

In the U.S., vat dyes are growing at the expense of other colors. Anthraquinone colors are largely responsible for this increased use, owing undoubtedly to their superior general fastness properties on cotton and viscose rayon. These two fibers constitute about 70% of the textile field on which the "vat dyed" label has gradually become known as a symbol of quality to the consumer.

Two classes of dyes accounted for 55.8% of all dyes produced in 1953. They are: vats, 60,957,000 lb. or 36.8%, and direct dyes, 31,495,000 lb. or 19%. In the five-year period 1947–1951, the average for vats was 60,280,000 lb. or 32.8%, for directs, 40,717,000 lb. or 21.8%. In 1952 the figures were: for vats, 57,189,000 lb. or 39.4%, and for directs, 26,805,000 lb. or 18.5%. In the vat totals, indigos accounted for 11.5% in 1947–51, 11.8% in 1952, and 10.8% in 1953. Of all classes, nonindigoid vat dyes showed the greatest increase in production, 11.5% from the period 1947–51 through 1953.

Fast vat dyes are sold in the U.S. under the following trade-marks. (A complete

list of dye trade-marks is given in the *Technical Manual and Yearbook* of the American Association of Textile Chemists and Colorists.)

Name	Manufacturer
Aheovat	Arnold Hoffman and Co.
Algol	General Aniline
Amanthrene	American Aniline Products
Calcoloid	American Cyanamid Co.
Calcosol	American Cyanamid Co.
Carbanthrene	National Aniline Division
Cibanone	Ciba Co.
Indanthrene	General Aniline
Mayvat	Otto B. May
Novanthrene	Nova Chemical Co.
Ponsol	Du Pont

In addition to the trade-marked names, somewhat different terminology is frequently applied to vat dyes. One common practice eliminates the producer's trade mark, leaving only the identifying stem. For example, Indanthrene Olive T or Ponsol Olive T may simply be referred to as Olive T. The same dye may also be referred to as Vat Olive T or Anthraquinone Vat Olive T.

The term "Indanthrene" in America or "Indanthren" abroad is a trade name reserved for vat dyes of the highest fastness properties. In usage today, the term has become synonomous with "very fast."

The production and sales of vat dyes as reported by the U.S. Tariff Commission for 1953 are shown in Table I.

TABLE I. U.S. Production and Sales of Important Vat Dyes for 1953.

			Sales		
C.I. No.	Dye	Production, thousands of pounds	Quantity, thousands of pounds	Value, thousands of dollars	Unit value
1100	Indanthrene Navy Blue BRP	965	855	1073	1.25
1101	Vat Jade Green	6506	5632	6294	1.12
113	Indanthrene Blue GCD	2475	2074	3251	1.57
1102	Vat Green B	2344	2225	1412	0.63
1113	Indanthrene Blue GCD	2475	2074	3251	1.57
1151	Indanthrene Brown R	852	686	1055	1.54
1151[a] 1150	Indanthrene Brown G	823	789	1076	1.36
1150	Indanthrene Olive R	782	770	879	1.14
Prototype No.					
118	Indanthrene Brown BR	1019	1005	1487	1.48
121	Indanthrene Khaki 2G	2591	2626	3585	1.37
291	Indanthrene Golden Yellow GK	833	513	1198	2.34
293	Indanthrene Olive Green B	2038	1665	2636	1.58
547	Indanthrene Olive T	1354	1368	1868	1.37
9	Algol Yellow GC	2269	2030	3033	1.49

[a] Mixture.

APPLICATION

Vat dyes are sold in both powder and paste form. The powder form has the advantage of being stable to prolonged storage, whereas pastes are subject to drying

out and freezing in cold weather. Undispersed powders must be prereduced for application and cannot be pigment-padded. Dispersed powders and pastes may be used for pigment padding and possess the additional property of being more easily vatted in a shorter time. This eliminates much of the work necessary for preparation of the vat as in the case of concentrated undispersed powders (8).

Several recent innovations in application are commercially quite important (see also *Dyes (application)*, Vol. **5**, p. 389). *Padding of cotton* with "vat acid" or hydrogen leuco dispersions of vat dyes has been practiced in recent times. The method has certain advantages in application, chiefly because the finely divided pigment dispersion, which lacks affinity for cellulose, may be evenly distributed throughout the cloth and can be converted to the alkali-soluble leuco ion at a predetermined stage (10,13). The process is restricted to pale and medium shades.

A recent development, *redox control*, is probably the most important advance in vat dye application to cotton and viscose in some years. Oxidation-reduction potential is measured during the dyeing process and controlled at the proper level by additions of caustic soda or hydrosulfite, $Na_2S_2O_4$. By this process uniform runs are made on large yardages with little variation in strength and shade from start to finish. Rejects and seconds are thus decreased to a much lower level than heretofore possible (11,18,19).

Chemical methods of oxidation-reduction control for the purpose of preventing dye decomposition have also been used with success in many operations. The most important agents for this purpose are sodium nitrite and dextrins.

Continuous vat dyeing by means of a molten metal bath, known as the *Standfast process*, has been developed recently. It is simple in principle. The cloth is impregnated with reduced vat liquor and passed into a hot molten bath of Wood's metal type at 200°F., where rapid penetration of the leuco takes place. The color is developed by standard oxidation methods. The method has not yet become a factor in vat dyeing in the U.S., but in England it has seen considerable use (15).

Many attempts have been made to dye cellulose acetate with vat dyes. None of these methods enjoys outstanding success today. Saponification of the fiber usually results, accompanied by a loss of hand. Swelling agents are used in some instances in combination with the vat process on acetate. By the use of ethanol in a mildly alkaline vat it is claimed that with selected colors heavy shades of excellent fastness on acetate are obtained (1).

For the dyeing of nylon, vat dyes are relatively unimportant. By increasing the dyeing temperature from 140–160°F. to 200–212°F. and substituting sulfoxylate for hydrosulfite, spun nylon is dyed in pastel to medium shades (12).

In every instance a vat dye exhibits worse lightfastness on nylon than on cotton. Lack of adequate lightfastness has limited the use of vats for this textile. If lightfastness is unimportant and washfastness desirable as in nylon hosiery, vats are used.

Vats have been applied to the newer synthetics by a continuous process through use of the *vat acid method* (14). Fastness properties vary but in general are good on Dacron (a polyester fiber), Acrilan and Orlon (polyacrylonitrile fibers), and Dynel (a polyacrylonitrile–polyvinyl chloride fiber) (see also *Textile fibers, synthetic*).

Union shades on blends of Dacron or Orlon with wool have been obtained through padding the union with an acrylonitrile latex and a vat paste followed by subsequent reduction and oxidation (6). Vat dyes in general are not used for wool alone because of the high alkalinity required, but indigo, for example, can be successfully applied by the Helindon method. (See Vol. **5**, p. 396.)

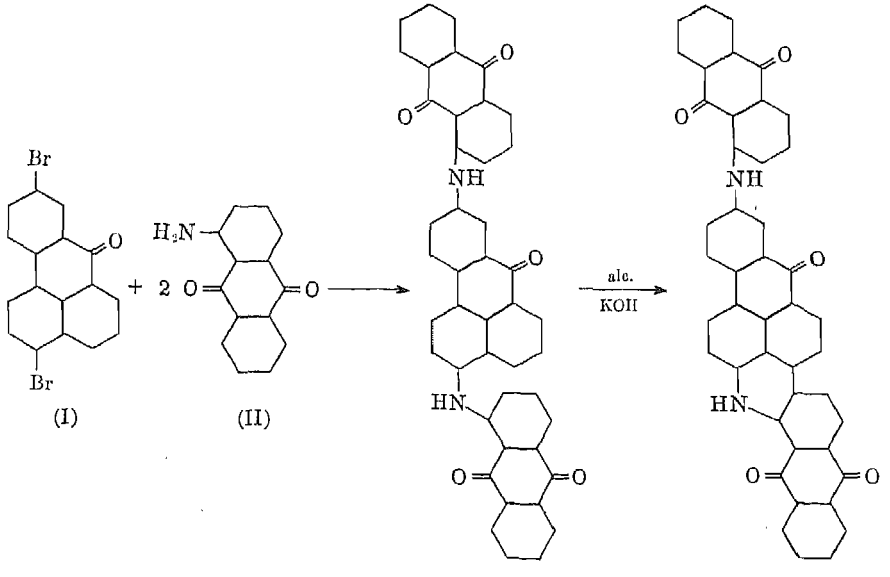
Polyester fibers, such as Dacron, have been effectively dyed with vats by the *Thermosol process* (9). In essence the method consists in padding the Dacron with a paste consisting of a thickener, a low-boiling organic solvent, and dispersed dye. The fiber is dried and the color is then developed by heat treating at about 400°F. For this method, indigoid classes are preferred.

Anthraquinone and Related Quinonoid Dyes

Nearly all the recent effort in vat dye research has been concentrated on anthraquinone and related quinonoid systems. For the most part, only the newer dyes will be discussed.

Valuable dyes are obtained from *benzanthrone* (7*H*-benz[*de*]anthracen-7-one). Thus **Indanthrene Olive Green B** (Pr. 293) is important as a vat green component where extreme lightfastness is required in conjunction with other good fastness properties (20). It is manufactured by the condensation of 3-bromobenzanthrone (13-bromobenzanthrone) with 1-aminoanthraquinone (II), followed by ring closure of this product in potassium hydroxide–methanol (see Vol. **1**, pp. 970–1, 977, formula (LV)). Another member of this benzanthrone (or acridine) class is **Indanthrene Olive T** (III) (Pr. 547). It is an important war-time color and is used in large volume. It is made by reactions of the same type as Indanthrene Olive Green B, starting with 3,9-dibromobenzanthrone (I) in place of 3-bromobenzanthrone (7, p. 140) (see Scheme 1).

SCHEME 1



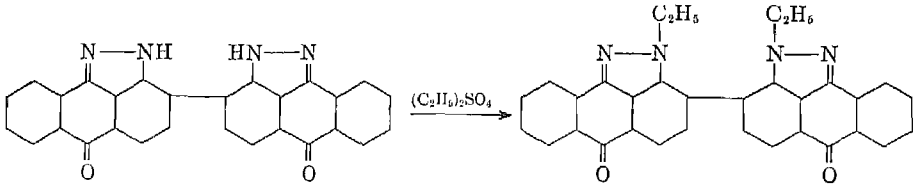
(III) Indanthrene Olive T (Pr. 547)

Of interest is the sulfur analog of Indanthrene Olive Green B. It is prepared by caustic fusion of 3-benzanthronyl 1-anthraquinonyl sulfide at 130°C. (23).

Important red dyes of the *pyrazoleanthrone* (anthra[1,9]pyrazole) class are obtained by alkylation of Pyrazoleanthrone Yellow (2,2′-dipyrazoleanthronyl, {3,3′-bianthra[1,9]pyrazole}-6,6′-(1*H*,1′*H*)-dione) (IV) (*C.I.* 1122), which is now important

only as an intermediate (see also Vol. **1**, p. 971). The best known is the diethyl derivative, **Indanthrene Rubine R Dbl.** (V) (Pr. 124) (21). (The positions of the ethyl groups as shown in (V) have been questioned (4).) Brightness of shade and great tinctorial power make this color outstanding.

SCHEME 2

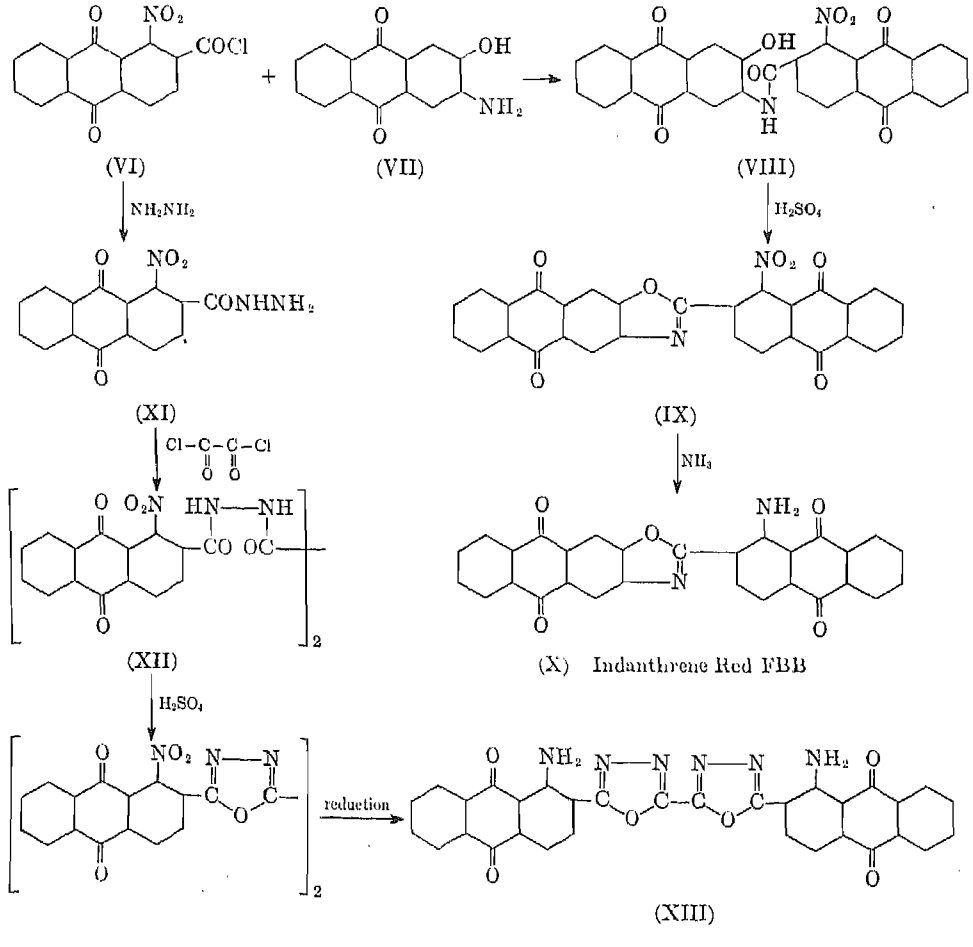


(IV) Pyrazoleanthrone Yellow (*C.I.* 1122)

(V) Indanthrene Rubine R Dbl. (Pr. 124)

An unusually lightfast series of bluish-red dyes is based upon 1-nitro-2-anthraquinonecarbonyl chloride (VI). **Indanthrene Red FBB** (X) (Pr. 296), an *oxazole*,

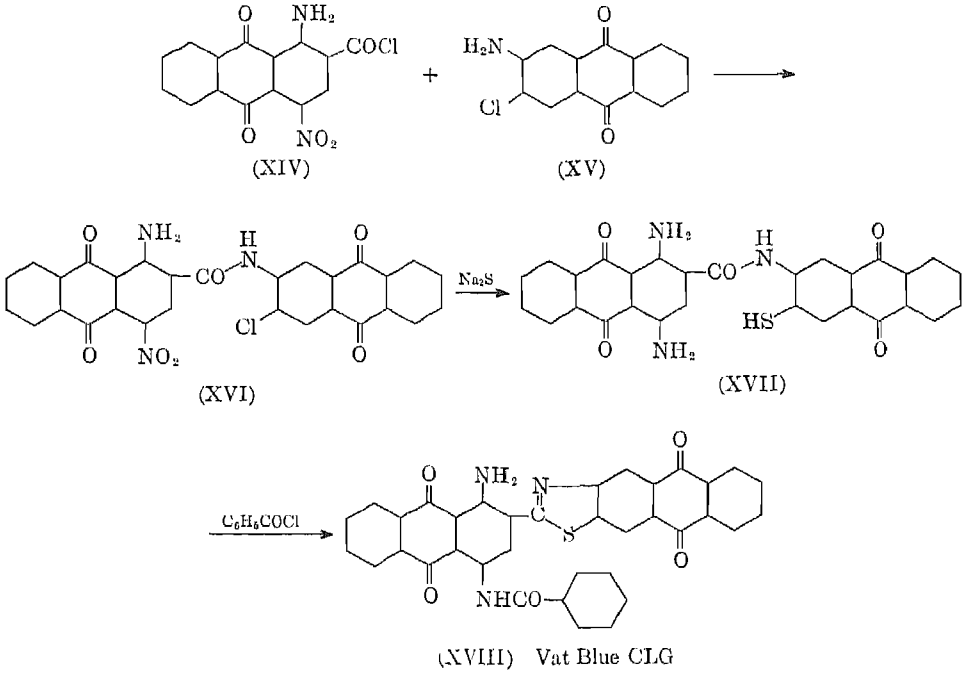
SCHEME 3



industrially important, is prepared by treating 2-hydroxy-3-aminoanthraquinone (VII) with 1-nitro-2-anthraquinonecarbonyl chloride. The resulting amide (VIII) is then cyclized in sulfuric acid to the oxazole (IX), which is aminated with ammonia under pressure to yield the dye (X). Recently patents have been issued on the very interesting oxadiazole structure derived primarily from the action of (VI) upon hydrazine (24,25). The resulting hydrazide (XI) coupled with a difunctional carboxylic acid derivative gives the bishydrazide (XII), which on acid ring closure and reduction yields a bisoxadiazole (XIII). See Scheme 3.

Vat Blue CLG (XVIII), a blue vat dye fast to chlorine, belongs with the *thiazole dyes* (*q.v.*). First, 1-amino-4-nitro-2-anthraquinonecarbonyl chloride (XIV) is condensed with 2-amino-3-chloroanthraquinone (XV) (see Scheme 4). The resulting

SCHEME 4



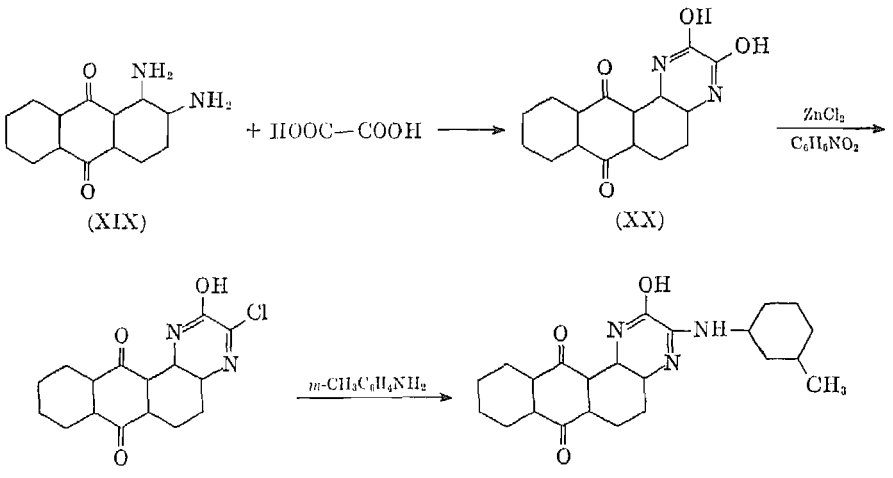
(XVIII) Vat Blue CLG

amide (XVI) is reduced by sodium sulfide, which also replaces the chlorine atom with a mercapto group. Benzoylation of this derivative (XVII) produces the cyclized dye (XVIII) (7, p. 68). (See Scheme 4.) Costly manufacture prevents large-scale demand for this color.

Vat Brilliant Scarlet RK (XXII) is an unusual vat dye possessing the *phthaloylquinoxaline* (naphtho[2,3-*f*]quinoxaline) nucleus. It has excellent fastness to light and is extremely bright in shade. The dye is synthesized by heating oxalic acid with 1,2-diaminoanthraquinone (XIX) at 150°C. (see Scheme 5). When the intermediate dihydroxyquinoxaline (XX) is treated with zinc chloride in nitrobenzene, a chlorohydroxyquinoxaline (XXI) is produced, which on condensation with *m*-toluidine produces the dye (XXII) (7, p. 97). After dyeing, this product requires an extended soaping to develop its color.

A heterocyclic family of yellow vat dyes of some interest are the *1,9-pyrimid-*

SCHEME 5

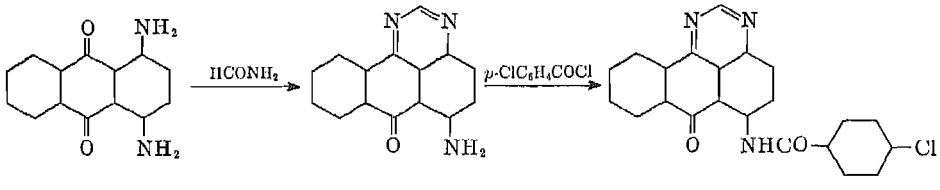


(XIX) (XX)

(XXI) (XXII) Vat Brilliant Scarlet RK

anthrones (7*H*-dibenzo[*de,h*]quinazolin-7-ones) substituted in the 6- or 8-positions with acylamino groups. One representative is a very bright greenish yellow, **Vat Yellow 7GK** (XXV). It is synthesized by the action of formamide on 1,4-diaminoanthraquinone (XXIII) to produce 6-amino-1,9-pyrimidanthrone (XXIV), which is acylated by *p*-chlorobenzoyl chloride to give the dye (XXV) (22) (see Scheme 6). Because of its only moderate lightfastness, the question has arisen as to whether the color deserves the Indanthrene rating under which it is marketed.

SCHEME 6

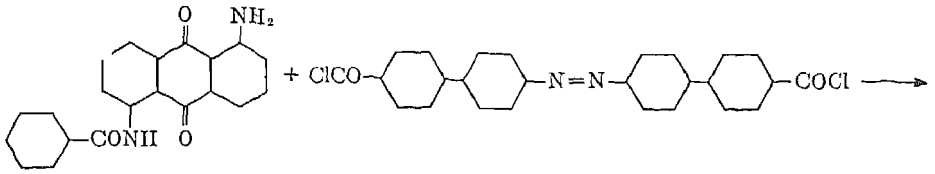


(XXIII) (XXIV) (XXV) Vat Yellow 7GK

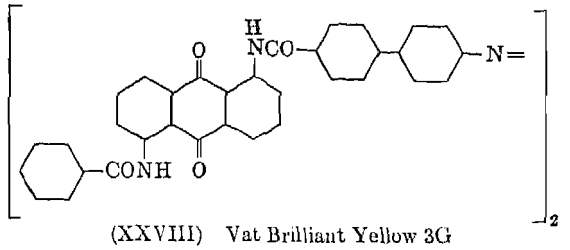
Vat Brilliant Yellow 3G (XXVIII) is unique among the anthraquinone amides because of its azo group. It is manufactured by the action of *p,p'*-azobiphenyldicarboxylic acid chloride (XXVII) on 1-amino-5-benzamidoanthraquinone (XXVI) (7, p. 178) (see Scheme 7). The remarkable resistance to reduction of the azo linkage of this compound is ascribed to the increased stability conferred by the bis(*p,p'*-biphenyl) system.

Acedianthrones (aceanthra[2,1-*a*]aceanthrylene-5,13-diones) are a newer type of polycyclic quinone and are unusual in that they possess two fused 5-membered rings. Typical is **Vat Red Brown 2R** (XXX), a dichloro derivative of good general properties. It is prepared through condensation of 2-chloroanthrone (XXIX) with glyoxal sulfate, followed by oxidation with alcoholic potassium hydroxide. Final ring closure is accomplished by heating in sulfuric acid (2, p. 127). See Scheme 8.

SCHEME 7

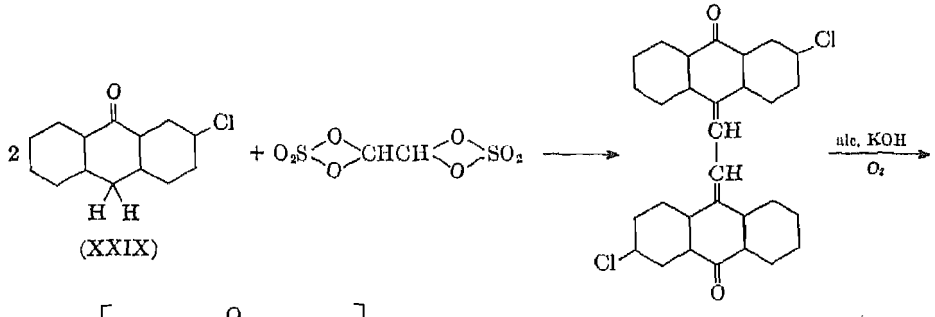


(XXVI) (XXVII)

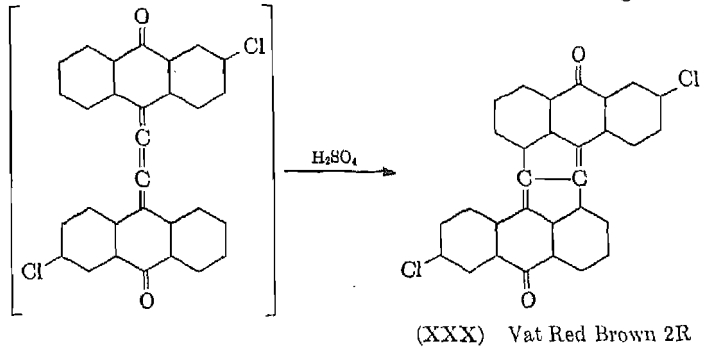


(XXVIII) Vat Brilliant Yellow 3G

SCHEME 8



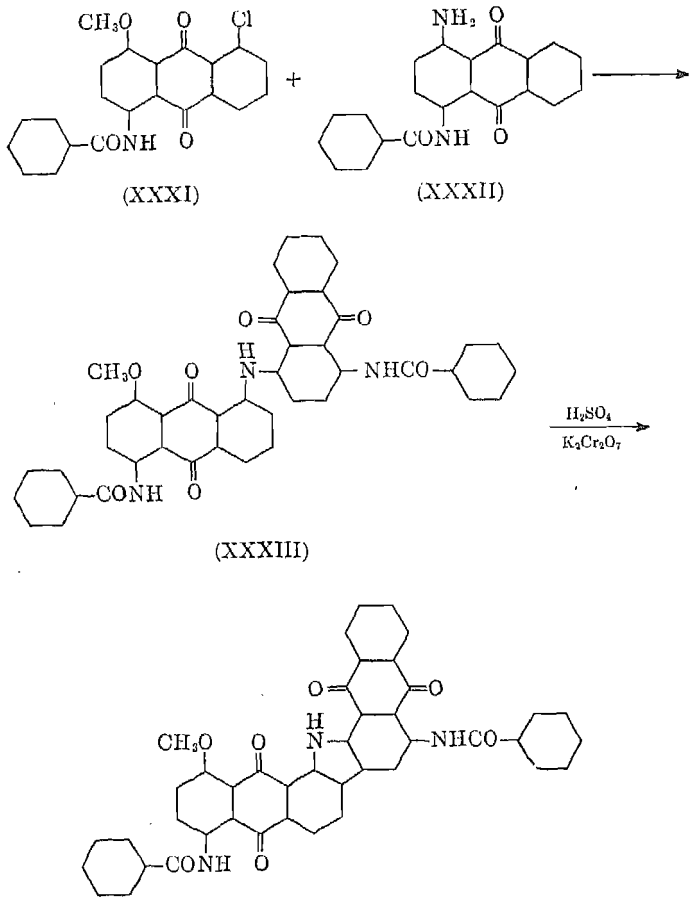
(XXIX)



(XXX) Vat Red Brown 2R

Valuable for the combination of its bright, reddish-brown shade with excellent fastness properties is **Indanthrene Red Brown 5RF** (XXXIV) (Pr. 448). This *carbazole dye* is synthesized by condensing 5-chloro-1-benzamido-4-methoxyanthraquinone (XXXI) with 1-amino-4-benzamidoanthraquinone (XXXII) to the dianthrimide (XXXIII), followed by carbazolation (3, p. 44) (see Scheme 9).

SCHEME 9

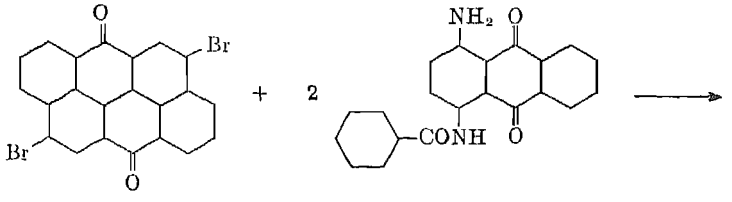


(XXXIV) Indanthrene Red Brown 5RF (Pr. 448)

Indanthrene Brilliant Orange RK (XXXV) (Pr. 116), a dibromo derivative of the *anthanthrone* (dibenzo[*cd*,*jk*]pyrene-6,12-dione) family (see Vol. **1**, p. 974), is the most important member in its class. It is used when an extremely lightfast, bright orange is required (7, p. 190). *Anthanthrimides* prepared from condensation of the halogen derivatives of anthanthrones with aminoanthraquinones are violet to gray in shade. An example is **Vat Gray BG** (XXXVI), which is manufactured by the condensation of 1-amino-4-benzamidoanthraquinone (XXXII) with Indanthrene Brilliant Orange RK (XXXV) (3, p. 23) (see Scheme 10).

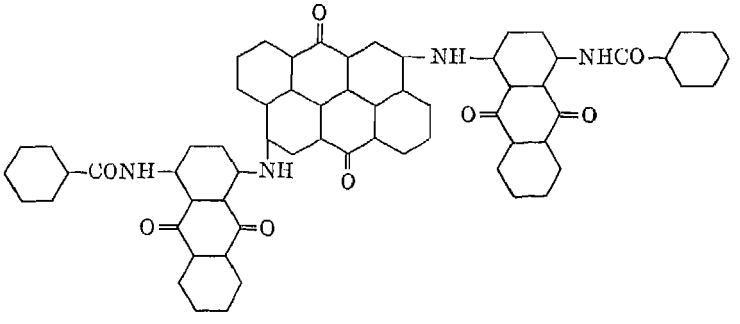
Indanthrene Direct Black RB (Pr. 289) is an important color of the *pyranthrone* class because of its good application properties. It is formed through the condensation of aminoviolanthrone (aminodibenzanthrone, an amino derivative of Indanthrene Dark Blue BD (*C.I.* 1099), see Vol. **1**, p. 970) and 1-aminoanthraquinone with tetrabromopyranthrone (a tetrabromo derivative of Indanthrene Golden Orange G (*C.I.* 1096, see Vol. **1**, p. 974). Very probably it is a mixture of all the compounds possible from such a reaction (7, p. 118).

SCHEME 10



(XXXV) Indanthrene Brilliant Orange RK (Pr. 116)

(XXXII)



(XXXVI) Vat Gray BG

Bibliography

(1) A.A.T.C.C., *The Application of Vat Dyes*, Monograph No. 2, p. 158, Mack Printing Co., Easton, Pa., 1953.
(2) *BIOS Final Rept.* **987.**
(3) *BIOS Final Rept.* **1493.**
(4) Bradley, K. J., *J. Chem. Soc.*, **1952,** 1636.
(5) Bradley, K. J., and Kronowitt, P., *Ind. Eng. Chem.*, **46,** 1146 (1954).
(6) Clemson College Student Chapter, *Am. Dyestuff Reptr.*, **43,** 48 (1954).
(7) *FIAT Final Rept.* **1313.**
(8) Fox, M. R., *Vat Dyestuffs and Vat Dyeing*, Wiley, N.Y., 1947, Ch. VIII.
(9) Gibson, J. W., *Am. Dyestuff Reptr.*, **42,** 1 (1953).
(10) Hennessey, J. H., *Am. Dyestuff Reptr.*, **36,** 775 (1947).
(11) Marnon, D. E., *Am. Dyestuff Reptr.*, **41,** 292 (1952).
(12) Meunier, P. L., and Saville, A. K., *Rayon Textile Monthly*, **28,** 272, 323, 379 (1947).
(13) Muller, J., *Am. Dyestuff Reptr.*, **39,** 113 (1950).
(14) Parks, W. G., *Am. Dyestuff Reptr.*, **41,** 223 (1952).
(15) Richardson, F. S., *Am. Dyestuff Reptr.*, **41,** 273 (1952).
(16) U.S. Tariff Comm. Repts., **194,** 22 (1954).
(17) Venkataraman, K., *The Chemistry of Synthetic Dyes*, Vol. II, Academic, N.Y., 1952.
(18) Zimmerman, C., Mecco, J. M., Fordemwalt, F., and Cooke, T. F., *Am. Dyestuff Reptr.*, **41,** 597 (1952).
(19) Zimmerman, C., Mecco, J. M., Fordemwalt, F., and Cooke, T. F., *Calco Tech. Bull.* 828.
(20) Ger. Pat. 212,471 (July 5, 1909), Badische Anilin; Friedl., **9,** p. 834.
(21) Ger. Pat. 301,554 (Sept. 24, 1917), Griesheim-Elekt.; Friedl., **13,** p. 407.
(22) Ger. Pat. 573,556 (March 16, 1933), I. G. Farbenind.; Friedl., **19,** p. 2021.
(23) U.S. Pat. 2,441,512 (May 11, 1948), M. Scalera (to American Cyanamid).
(24) U.S. Pat. 2,464,831 (March 22, 1949), F. Stilmar (to Du Pont).
(25) U.S. Pat. 2,511,018 (June 13, 1950), F. Stilmar (to Du Pont).

D. I. RANDALL

VEGETABLE BUTTERS. See *Fats and fatty oils*, Vol. **6**, p. 148.

VEGETABLE BLACKS. See *Pigments (inorganic)*, Vol. **10**, p. 653.

VEGETABLE DYES. See *Colors for foods, drugs, and cosmetics*, Vol. **4**, p. 311; *Dyes*, Vol. **5**, p. 345; *Furs and fur processing*, Vol. **7**, p. 46; *Tints, hair dyes and bleaches*, Vol. **14**, p. 169.

VEGETABLE OILS. See *Fats and fatty oils.*

VEGETABLES. See *Food and food processing*; *Food analysis*, Vol. **6**, p. 832.

VEGETABLE TANNING; VEGETABLE TANNING MATERIALS. See *Leather and tanning*, Vol. **8**, p. 297; *Tanning materials (vegetable).*

VENEERS. See *Plywood.*

VENTURI METER. See *Fluid mechanics (flow measurement)*, Vol. **6**, p. 645.

VENTURI SCRUBBER. See *Sprays*, Vol. **12**, p. 720.

VERATRALDEHYDE, $(CH_3O)_2C_6H_3CHO$. See *Phenolic aldehydes*, Vol. **10**, p. 324.

VERATROLE, o-$C_6H_4(OCH_3)_2$. See *Phenolic ethers*, Vol. **10**, p. 331.

VERATRUM (ALKALOIDS); VERATRINE; VERATRIDINE, $C_{36}H_{51}NO_{11}$. See *Alkaloids*, Vol. **1**, p. 502; *Cardiovascular agents*, Vol. **3**, p. 223; *Stimulants and depressants of the nervous system*, Vol. **13**, p. 41.

VERDIGRIS, NEUTRAL, $Cu(C_2H_3O_2)_2.H_2O$; **VERDIGRIS, FRENCH,** $Cu(C_2H_3O_2)_2.CuO.6H_2O$. See *Copper compounds*, Vol. **4**, p. 468; *Pigments (inorganic)*, Vol. **10**, p. 648.

VERMICULITE. See *Insulation, thermal*, Vol. **7**, p. 932; *Refractories*, Vol. **11**, p. 602; *Silica and silicates (mineral)*, Vol. **12**, pp. 279, 291.

VERMOUTH. See *Wines.*

VERNOLIC ACID, $CH_3(CH_2)_7CHOHCH{:}CH(CH_2)_6COOH$. See *Fatty acids (hydroxy and keto)*, Vol. **6**, p. 288.

VESICANTS. See *Gas warfare agents*, Vol. **7**, p. 121.

VESUVIANITE, $Ca_{10}Al_4(Mg,Fe)_2Si_9O_{34}(OH)_9$. See *Silica and silicates (mineral)*, Vol. **12**, pp. 279, 301.

VETIVENE, $C_{15}H_{24}$; **VETIVEROL, VETIVENOL; VETIVER ACETATE.** See *Terpenes (sesqui-)*, Vol. **13**, pp. 743, 746.

VETIVER OIL. See *Oils, essential*, Vol. **9**, p. 590.

VETIVONES, $C_{15}H_{22}O$. See *Terpenes (sesqui-)*, Vol. **13**, pp. 745, 750.

VICKERS HARDNESS TEST. See *Hardness*, Vol. **7**, pp. 363, 365.

VINEGAR

Vinegar is a condiment prepared by two separate microbial processes, first an alcoholic fermentation of various raw materials, containing either naturally occurring or converted fermentable sugars, by species of yeasts of the genus *Saccharomyces*, and second, the so-called oxidative fermentation of alcohol so produced by species of bacteria of the genus *Acetobacter*. (See *Acetic acid*; *Enzymes*; *Fermentation*.)

Although cull apples and apple peels and cores are the most important economic raw material in the U.S., grapes and grape products, barley malt, honey, and various cull fruits (fresh and dried) may be used for the production of table vinegar. Industrial alcohol is the most important source of vinegar for use in mayonnaise, tomato products, prepared mustard, pickles, sauces, and other products. Specially flavored vinegars are prepared by infusion of cider or wine vinegar with herbs and spices such as garlic, eschalots, tarragon, etc.

There is no standard of identity for vinegar under the Food, Drug and Cosmetic Act of 1938. Under the Federal Food and Drugs Act of 1906, in the latest effective service and regulatory announcement of 1933, the following six types of vinegar are defined (22):

"1. Vinegar, cider vinegar, apple vinegar, is the product made by the alcoholic and subsequent acetous fermentations of the juice of apples, and contains, in 100 cubic centimeters (20°C.), not less than 4 grams of acetic acid.

"2. Wine vinegar, grape vinegar, is the product made by the alcoholic and subsequent acetous fermentations of the juice of grapes, and contains, in 100 cubic centimeters (20°C.), not less than 4 grams of acetic acid.

"3. Malt vinegar is the product made by the alcoholic and subsequent acetous fermentations, without distillation, of an infusion of barley malt or cereals whose starch has been converted by malt, and contains, in 100 cubic centimeters (20°C.), not less than 4 grams of acetic acid.

"4. Sugar vinegar is the product made by the alcoholic and subsequent acetous fermentations of sugar syrup, molasses, or refiners' syrup, and contains, in 100 cubic centimeters (20°C.), not less than 4 grams of acetic acid.

"5. Glucose vinegar is the product made by the alcoholic and subsequent acetous fermentations of a solution of glucose, is dextrorotatory, and contains, in 100 cubic centimeters (20°C.), not less than 4 grams of acetic acid.

"6. Spirit vinegar, distilled vinegar, grain vinegar, is the product made by the acetous fermentation of dilute distilled alcohol, and contains, in 100 cubic centimeters (20°C.), not less than 4 grams of acetic acid."

The composition of vinegar will depend upon: the nature of raw material that is converted to vinegar stock; the materials added to facilitate alcoholic fermentation (such as nitrogenous, phosphate, and potassium compounds added to products deficient in these, for example, honey, and sulfurous acid or sulfites added to control the alcoholic fermentation); the materials added to facilitate acetification (usually growth and activity stimulants for *Acetobacter* such as yeast hydrolyzates, B-vitamin concentrates, and phosphates); and the extent of alcoholic and subsequent acetic fermentation. The early standards for vinegars, particularly cider vinegar, prohibited the use of fruit waste accumulating in other industries, such as apple peels and cores from apple sauce and dried apple production. To prevent the use of these products and adulteration of a fruit vinegar such as cider vinegar with vinegars from another source or ad-

dition of acetic acid or water, the early definition of vinegar (21) specified a minimum apple solids and apple ash content. The early standard specifying the presence of not less than 1.6 g. of apple solids and not less than 0.25 g. of apple ash was so impractical that it actually compelled the manufacturer of high-grade cider vinegar to adulterate his product to meet the requirements. Present standards are more realistic and allow the manufacture of cider vinegar not only from the juice of whole apples but also from the juice of sound apple peels and cores. The historical evolution of present standards is discussed by Tolman (21), Brooks (6), and Mitchell (14), and the present position by Herrick (10).

The most widely quoted data (see ref. 6) on the composition of cider vinegar are those of Balcom (3). They are given in Table I. In comparison with cider vinegar, the average solids content of wine vinegar is 1.89%, malt vinegar 2.70%, and distilled vinegar 0.35%. The ash content for these vinegars is 0.27, 0.34, and 0.04%, respectively; and the P_2O_5 content, in comparison with 0.035% for cider vinegar, is 0.053, 0.105, and 0.0%, respectively, for the others.

TABLE I. Composition of Cider Vinegar.

Constituent	Average	Max.	Min.
Total acid as acetic, %	4.94	7.96	3.29
Total solids, %	2.54	4.52	1.37
Nonsugar solids, %	1.90	2.89	1.26
Reducing sugars in solids, %	19.6	45.0	5.6
Total ash, %	0.367	0.52	0.20
Alkalinity of water-soluble ash, ml. 0.1*N* acid[a]	35.7	56.0	21.5
Ash in nonsugar solids, %	18.8	26.5	11.2
Soluble phosphoric acid (mg. P_2O_5)[a]	17.3	39.9	6.7
Insoluble phosphoric acid (mg. P_2O_5)[a]	29.3	64.2	15.1
Alcohol by volume, %	0.35	2.0	0.03
Glycerol, %	0.30	0.46	0.23
Polarization (direct), °V	−1.46	−3.6	−0.2
Polarization (invert), °V	−1.69	−3.1	0.0

[a] Ash from 100 ml. vinegar.

In addition to acetic acid, vinegars contain variable amounts of: nonvolatile organic acids (chiefly malic and citric acids with smaller amounts of succinic and lactic acids; formic acid may be present in distilled vinegar); glycerol; unfermented and unfermentable sugars; unoxidized alcohol and acetaldehyde; acetoin (acetylmethylcarbinol); and phosphates, chlorides, and sulfates of potassium, calcium, and other cations. The analysis of vinegars at present (2) includes the determination of total solids content, total and water-soluble and insoluble ash content, alkalinity of soluble ash, total and soluble and insoluble phosphate, total acid content, volatile acid content, total reducing substances before and after inversion, nonvolatile and volatile reducing substances, alcohol, glycerol, coloring matter, polarization, sulfate, heavy metals, dextrin, preservatives, and permanganate oxidation number. From these analyses, interpreted in terms of the known variability of authentic vinegars, it is possible to determine the type and extent of adulteration. The permanganate oxidation number is particularly useful for differentiating between vinegar and commercial acetic acid. The nonvolatile reducing substances are useful in calculating nonsugar solids.

The permanganate or oxidation number, usually reported as milliliters of 0.01 *N*

permanganate required to oxidize the distillate from 100 ml. of sample in 30 minutes, is a measure of volatile reducing substances, chiefly acetylmethylcarbinol (3-hydroxy-2-butanone), $CH_3COCHOHCH_3$, formed during fermentation and not present in synthetic acetic acid. The volatile reducing substances expressed as invert sugar range from 0.14 to 0.34 g./100 ml. in cider vinegar. The permanganate number as a measure of the content of volatile carbonyl compounds, unsaturated organic acids, and secondary alcohols is discussed in detail by Saruno (16a). Recent data on acetylmethylcarbinol content of vinegar are given by Doro and Sadini (7a).

The strength of vinegar (the concentration of acetic acid) was expressed historically in terms of the grains of sodium bicarbonate neutralized by one fluid ounce wine measure of vinegar, and in the early vinegar testers this was measured by the volume of carbon dioxide gas evolved from excess of sodium bicarbonate treated with a measured volume of vinegar. The original grain strength multiplied by 0.1565 gave the concentration of acid as acetic acid in grams per 100 cu.cm. Although the term "grain strength" is still commonly used to express the concentration of the acetic acid in a vinegar, one-grain vinegar is defined now as containing 0.1 g. of acetic acid in 100 ml. at 20°C. The present grain strength is thus ten times the acetic acid content. A vinegar meeting the legal minimum of 4 g. acetic acid per 100 cu. cm. would be of 40 grain strength in comparison with the old standard of 25.6 grain strength.

Manufacture

ALCOHOLIC FERMENTATION

The conversion of the sugars in fruit juices or other sugar-containing media, or of cereal starch after enzymic or acid hydrolysis into sugar, to acetic acid is carried out in two stages. In the first stage the sugars are fermented to alcohol through the agency of enzymes of yeast. In this alcoholic fermentation sugar is converted chiefly into ethyl alcohol and carbon dioxide, part of the sugar is assimilated by the yeast cells, and part is transformed into glycerol, acetaldehyde, lactic acid, and so on. The succinic acid that accumulates in the alcoholic fermentation is derived largely from carbon dioxide and oxalacetic acid, the higher alcohols from the amino acids, and 2,3-butylene glycol (2,3-butanediol) from acetaldehyde. According to the Gay-Lussac equation (5):

$$C_6H_{12}O_6 = 2\ CO_2 + 2\ C_2H_5OH$$

1 g. of glucose should yield 0.5114 g. of alcohol. The yield of alcohol is usually only about 85–90% of the stoichiometrical yield, but recent experiments with five strains of compressed bakers' yeast and five strains of brewers' yeast and pure D-glucose gave fermentation efficiencies of 88–94%. The fermentation efficiency, the ratio of the amount of alcohol obtained from the weight of sugar fermented to the theoretical yield, was found to be greater with proliferating yeasts than with resting cells, and actively fermenting yeast gave a slight but significant increase in fermentation efficiency. To obtain optimum yields of alcohol and to prevent undesirable changes in quality as a result of contamination with undesirable species of yeast and bacteria, the fermentation is conducted at a temperature of 75–80°F., with a starter of a selected strain of *Saccharomyces cerevisiae*, and in the presence of the minimum amount of sulfur dioxide. The raw material used is prepared for alcoholic fermentation by conversion of starches into fermentable sugars and extraction of these sugars, expression of juice

from products such as fresh fruits, and dilution of honeys, sirups, or dried fruits with water. The fermentable sugar content of the product is adjusted to not less than 8% nor over 20%. Where necessary, potassium, phosphate, and ammonium salts are added, as for example with honey, which is low in these originally and whose content of these is further reduced by the dilution necessary for fermentation. Ammonium and potassium phosphates are not required in the fermentation of crushed grapes and grape juice or with apple juice. Apple juice usually ranges from 10 to 15% in sugar content, but it may be as low as 6.5%, particularly when expressed from peels and cores. Apple juice of low sugar content should be blended with juice of higher sugar content to obtain vinegar of 50–60 grain strength. Concentrated apple juice may be used as blending stock for juices low in sugar content and also for the production of higher strength cider vinegar. To facilitate the fermentation of apple juice concentrated by vacuum evaporation it is necessary to add ammonium phosphate, particularly at lower fermentation temperatures.

The alcoholic fermentation is conducted usually in two stages: the primary stage, which normally lasts from 3 to 7 days, during which the bulk of the sugar is converted into alcohol, and the subsequent slower and less active fermentation, which extends over a period of several weeks. The primary fermentation is usually conducted in open fermenting vats with cooling coils or external coolers to facilitate control of temperature and to follow the course of fermentation by periodic determination of Brix degree. The secondary fermentation is conducted in closed fermentors to prevent spoiling by aerobic yeasts and acetic acid bacteria. Sulfur dioxide as liquid sulfur dioxide or as sodium or potassium metabisulfite is added to the apple juice or other sugar-containing medium at the start of fermentation and before addition of the yeast starter to inhibit the growth and activity of undesirable yeasts and bacteria. An initial level of 50–100 mg. of sulfur dioxide per liter is sufficient. Although it is possible to convert fermented fruit juices containing up to a total of 100 p.p.m. of sulfur dioxide, it is better to keep the total and free sulfur dioxide content to 50 p.p.m. or less. When the alcoholic fermentation is completed, the yeast cells and other suspended material settle and the clarified wine is separated from the sediment by racking (drawing off). This stock may then be stored for additional aging or used directly for acetification.

Usually only apple juice is fermented by vinegar producers; grape and other fruit wine is purchased from wineries, beer and fermented malt from breweries or yeast plants, and distilled alcohol from distilleries. Fermented apple juice, and wine used for vinegar stock, are usually denatured by addition of sufficient strong vinegar to bring the acetic acid content to 1% in order to facilitate storage and to avoid payment of internal revenue wine tax. Alcohol for vinegar stock is also denatured with acetic acid. The added acetic acid also serves to protect the vinegar stock against spoilage by lactic acid bacteria if it is to be stored. Small quantities of sulfur dioxide may be used for this purpose also if the final sulfur dioxide content after fermentation is low enough to permit this without exceeding the concentration toxic to acetic acid bacteria used in converting this stock into vinegar. The vinegar stock should be low in reducing sugar content, preferably below 0.3%.

ACETIC FERMENTATION

The conversion of alcohol to acetic acid according to the overall reaction:

$$C_2H_5OH + O_2 \longrightarrow CH_3COOH + H_2O$$

is catalyzed by enzymes secreted by species of *Acetobacter*. It requires oxygen and, like the alcoholic fermentation, is exothermic. Theoretically 1 g. of alcohol should yield 1.304 g. of acetic acid, but in practice 1 g. of acetic acid is obtained, and only under exceptional circumstances is a yield of 1.1 g. attained. Thus, although a fermentation efficiency of 90% can be attained in the alcoholic fermentation (7,23), a fermentation efficiency of 77–84% is attained in the acetification process, with fruit vinegars. With distilled vinegars higher efficiencies can be attained industrially. Thus, Allgeier *et al.* (1), in pilot plant vinegar generators, obtained fermentation efficiencies on the basis of alcohol in the charge (denatured alcohol containing ethyl acetate), varying from 79.8 to 90.3%, when the water used in dilution of alcohol was varied. With the best water supply used, fermentation efficiencies of 85–90% were obtained. If the conversion of sugar into alcohol is 90% of the theoretical and the conversion of alcohol into acetic acid is 80% of the theoretical, apple juice used for vinegar production must contain not less than 8.32 g. of fermentable hexose per 100 ml. to yield a vinegar meeting the legal limit of 4 g. of acetic acid per 100 cu.cm. at 20 °C.

The vinegar stock for the production of 40 grain strength table cider vinegar is adjusted to an alcohol content of not less than 3 g. of alcohol and 1 g. of acetic acid per 100 ml. For the production of distilled vinegar of 100 grain strength the stock is adjusted to about 10.5% alcohol by volume and 1% acetic acid. Allgeier *et al.* (1), using 190-proof alcohol diluted with water to 9 g. of alcohol per 100 ml. of fluid, obtained vinegar of 9.9–10.6 g. of acetic acid per 100 ml. High-strength apple and wine vinegars can be made from stock of 10% alcohol and 1% acetic acid content by the generator process. The apple vinegar stock is adjusted either by dilution with water or blending of several stocks of high and low alcohol content. Wine is diluted with water to the desired alcohol strength and adjusted as to acetic acid content by addition of strong vinegar. To meet the present standards of identity the acetic acid content of a particular vinegar stock must be derived from vinegar prepared previously from similar stock; that is, cider vinegar cannot be added to wine or wine vinegar to apple cider stock. The distilled vinegar stock must be fortified with added growth stimulants to promote acetification, and, when necessary, similar preparations may be added to cider or wine vinegar stock.

Until recently the growth stimulants required by *Acetobacter* were not known, and several empirically developed nutrient mixtures distributed under trade names such as Aceto-pep were used at the rate of 2–3 lb./100 gal. of vinegar stock. These nutrients usually contain inorganic salts and malt or yeast extract. Allgeier *et al.* (1) reported that a filtered fermented solution of a diluted malt concentrate added at the rate of 1% by volume was quite satisfactory for the acetic fermentation of solutions of denatured alcohol. The nutritional requirements of several species of *Acetobacter* are now known (8,15a,16), but this knowledge has not yet been applied to the selection of the best growth and *activity stimulants* in vinegar production. Rao and Stokes (16) reported recently that, although *Acetobacter suboxydans* and *A. melanogenum* cannot grow in chemically defined media with ethyl alcohol as the sole source of carbon, they will develop when small amounts of yeast autolyzate, liver extract, or peptone are added to the medium. The growth-promoting activity of these biological materials is believed by these authors to be due to the reducing sugars and related substances which they contain. Small amounts of glucose, fructose, mannitol, and glycerol were substituted successfully for yeast autolyzate.

Recent investigations in Belgium (reported in *Food Engineering*, **27**, No. 2, 175

(1955)) indicate that, in laboratory generators charged with beechwood shavings and inoculated with *Acetobacter xylinum*, glucose, but not maltose, sucrose or invert sugar, is required for maximum acetification. The concentrations of glucose and other nutrients for optimum acetification, per liter, were: glucose, 0.5–0.7 g.; ammonium, 20 mg.; phosphate, 120 mg.; magnesium, 5 mg.; potassium, 15 mg. In commercial generators the addition of glucose did not increase the rate of acetification but did increase the yield of acetic acid and reduced carbon dioxide formation. The requirement of the other nutrients was confirmed.

A number of varieties of *Acetobacter* are described in the literature, but the particular species and strain possessing the characteristics desired for vinegar production in the *quick vinegar process* now generally used had not been isolated until very recently. Pure cultures of the several species of *Acetobacter* that have been isolated previously from vinegar do not have the desired characteristics, and vinegar generators as yet are not inoculated with pure cultures. A suitable quantity of unpasteurized vinegar obtained from a generator in satisfactory production is used to start a new generator.

Owing to difficulties encountered in culturing *Acetobacter* from operating generators, the bacteria actually active in acetic acid production have not been isolated and the changes in bacterial flora and bacterial activity during vinegar production under industrial conditions, until very recently, were still unknown. Shimwell (18) recently succeeded in isolating a pure culture of the "true working bacteria" in a vinegar acetifier and has described its morphological, cultural, and physiological characteristics. He considers this strain as belonging to the "mesoxydans" group of Fratem's classification. The pure culture was used successfully in making spirit, malt, and wine vinegars and was found to retain its acid tolerance and other desirable properties on prolonged subcultivation. The pure culture, unlike the mixed flora of unknown nature, gave a faster rate of acetification, gave a more uniform product, and resulted in elimination of undesirable contaminants.

The dehydrogenation of ethyl alcohol to acetic acid by the endocellular alcohol dehydrogenase of *Acetobacter* is greatly influenced in rate and extent by the species and strain of predominant bacteria and by the environmental conditions under which this conversion is allowed to occur. The concentration of bacterial cells relative to the volume of vinegar stock being converted, the method of controlling the diffusional operations involved in the mass transfer of the vinegar stock to the bacterial surface and of removal of the vinegar formed, the method of supplying the concentration of oxygen required for this oxidation, the temperature at which the oxidation occurs, and the composition of the vinegar stock markedly affect the rate, extent, and efficiency of acetification.

At the present time most commercial vinegar is produced by the generator process, in which the vinegar stock is pumped into specially devised distributors from which it is uniformly sprayed over the surface of an inert porous medium or packing material at the surface of which it is oxidized by the bacterial enzymes. The stock flows from the packing by gravity into receiving tanks from which it is recycled. The rate and extent of acetification in these generators are controlled by the rate of flow of the vinegar in the recycling process, the type and concentration of nutrients present or added, the overall size of the generator (alcohol conversion usually is slower in smaller generators), the extent of aeration, and the temperature. The slower acetification which occurs in the Pasteur modification of the *Orleans process*, in which a specially

constructed wooden grating is placed at the surface of the liquid in partly filled barrels or in shallow tanks to support the film of vinegar bacteria, is still used in Europe for wine vinegar production but has not been used extensively in the U.S. even for wine vinegar production. At one time it was believed that the generator process could not be used for the production of red wine vinegar because of excessive oxidation of anthrocyanin pigments, but by proper control of temperature and aeration this difficulty has been overcome.

The design and operation of vinegar generators have been based largely on empirical observations, rather than on scientific studies of the mass transfer operations involved in the conversion of alcohol into acetic acid, the factors influencing the efficiency of the oxidation process, and the production of vinegar of improved aroma and stability. The manufacture of vinegar is very ancient in origin and, as Bitting (4) pointed out, very little change in vinegar production occurred from the first complete description of vinegar production by Olivier de Serres in 1616 until the first development of the quick (generator) process by Schützenbach in 1823. Schützenbach provided ventilating holes near the bottom of the large tank used to hold the stock, which was distributed over the packing material for the purpose of obtaining a greater supply of air. Gravity flow was used for the liquid trickling down the packing material and for the air flowing up the tank. Bitting (4) presented a synopsis of the U.S. patents issued on various modifications of the generator process from 1849 to 1929. No important advance was made in the generator design, however, until Frings introduced his airtight generator in 1932 (7,9,11,14,19,24). In this generator cooling coils are provided in the collection chamber at the bottom for temperature control, and the oxygen supply is controlled by a damper located at a vent pipe at the top of the tank and by the number and size of air inlets at the lower part of the generator. The rate of flow of the stock through the generator is controlled by the rate of pumping of the vinegar stock from the collection chamber to the sprayer or distributing arm at the top of the generator packing. This generator has since been improved by installation of air blowers to control supply and distribution of air, better distribution of stock over the entire volume of packing, and improved temperature controllers. Automatic control of air and liquid flow and temperature was introduced in 1939 (15). Aside from patents, few data have been published on the operation of vinegar generators until that reported by Allgeier *et al.* (1) and Hromatka and Ebner (13). Hromatka and Ebner (13) investigated the oxygen requirements of *Acetobacter* on beechwood shavings and found that the oxygen uptake was linear with time at more than 12% of oxygen in the gas phase, but the rate of oxygen uptake dropped at lower partial pressures and reached zero at 4.5% of oxygen in the gas phase. Pure oxygen was not found to be harmful in generator fermentation but was harmful in submerged fermentation.

Frings Generator. The Frings generator consists of an airtight tank usually 14 ft. in diameter and 15 ft. high. Inside the tank near the bottom is a wooden grating, and near the top is the sprayer or distributing arm. At the top a 4-in. vent with a damper connected to a tile exhaust or a vapor-liquid separator serves to control the air supply. Air enters the generator through 10 air intakes, containing air filters, located around the tank near the level of the wooden grate. Tubular cooling coils are located at the bottom of the tank in the collection chamber, and these are connected by a centrifugal pump to a feed line supplying the sprayer. The generator is packed with beechwood shavings, supported by the wooden grating, up to about 1.5 ft. from the top of the generator. The vinegar stock or mix is allowed to circulate repeatedly through

the beechwood shavings until vinegar of the desired strength has been obtained. The cycle time in such a generator for distilled vinegar is usually 3–5 days in a good operation for a mix containing 9 g. of alcohol per 100 ml. of feed. In the Frings-type pilot plant vinegar generator used by Allgeier *et al.* (1952), in which the cycle time was deliberately increased to 7 days by decreasing nutrients slightly in order to allow one operator to carry out the experimental work, the rate of liquid flow was 12 gal./hr./100 cu.ft. of packing, and the rate of air flow was 55 cu.ft./hr./100 cu.ft. of packing when the operating temperature was approximately 85°F. The feed temperature was adjusted to 28°C., the average temperature at the upper level of the generator was 29°C. and at the lower end 30–32°C. Under these conditions the rate of production of acetic acid was 11 lb./24 hr./100 cu.ft. In a large Frings generator a 2500-gal. batch of mix containing 10.5% ethyl alcohol, 1% acetic acid, and 7 lb. of Aceto-pep requires 3–5 days to reach 10.5% acetic acid. In comparison the production of cider vinegar is assumed to be 0.2–0.3 gal. of 6% vinegar in 24 hr. per cubic foot of packing.

Theoretically 1 gal. of vinegar stock containing 11% alcohol by volume would require about 28 cu.ft. of air for oxidation of alcohol to acetic acid and would generate about 3300 B.t.u. In a closed generator such as the Frings the heat evolved in this oxidation would rapidly raise the temperature considerably above the desirable range of 80–90°F. Actually much more than the stoichiometric amount of air is required in the process and an adequate supply of cooling water must be supplied for the required temperature control.

In recirculating generators, even when inoculated with the desired flora by the use of carefully selected raw vinegar, difficulty is experienced with wine or cider vinegar owing to sliming caused by the development of the so-called "mother of vinegar," actually exocellular bacterial cellulose which encapsulates the bacterial cells.

Plugging of Frings-type generators may result also owing to slime formation occurring when the nutrients are not balanced properly. This sliming occurs more frequently when beechwood shavings are used as packing, but even with coke packing sliming occurs in 6–12 months of use, necessitating repacking. Slime formation is considerably decreased as the acetic acid content of the finished vinegar is increased, so that, with cider or wine vinegar stock containing sufficient alcohol to produce 10% vinegar, sliming occurs less frequently. Distilled-vinegar generators will operate indefinitely without being plugged with cellulose slime formed by *Acetobacter* when maintained in proper balance with nutrients under optimum conditions for normal operation. In the generation of lower-strength cider or wine vinegars the generators are packed with coke, rattan bundles, or corn cobs. When the generator becomes so plugged as to be uneconomical to operate, the packing is removed and thoroughly cleaned.

Beechwood shavings, properly curled, provide a good surface for growth and activity of *Acetobacter* species and are sufficiently inert and porous to allow for good operation of generators. They are, however, more expensive and more difficult to clean when plugged with slime.

Although beechwood shavings are the preferred packing for modern generators of the circulating type, the type of packing has varied considerably. Often the most readily available or cheapest packing obtainable in a given district has been used, such as coke, pumice, rattan, grape and other twigs, and corn cobs. Crushed coke, size graded to remove fine particles and dust, is a cheaper substitute, is more inert and easily cleaned, but is difficult to wash free of acid-soluble iron and copper salts. Metallic

contamination is undesirable not only because it renders the vinegar more susceptible to formation of hazes and deposits but also because it affects the acetification process. Allgeier *et al.* (1) reported that lead, copper, iron, zinc, and tin, when present in the vinegar at levels of 10, 15, 50, 100, and over 100 p.p.m., respectively, were toxic to vinegar bacteria and caused decrease in efficiency of conversion of ethyl alcohol to acetic acid, accompanied in most cases by a corresponding rise in residual alcohol.

Allgeier *et al.* (1) have recently reported comparative data on the performance of generators packed with beechwood shavings, coke, rattan, and Berl saddles. Surface area and impurities in coke were found to be limiting factors. Removal of impurities by acid washing, increasing the surface by using smaller pieces (¼ to ½ in. in diameter), and proper addition of nutrients to facilitate growth and adherence of bacteria to the surface increased the operating efficiency of the coke-packed generator from 76 to 98% of that obtained with beechwood shavings. A higher concentration and a different type of nutrient were required with coke than with beechwood packing. The coke-packed generator responded markedly to yeast autolyzate – steep water mixture. With specially prepared rattan, yeast autolyzate also produced marked improvement in operating efficiency. The nutrient requirements were found to change with type of packing, special nutrients being required by packings deficient in extent of surface or by packings with surfaces not readily coated with bacteria.

Submerged Fermentation. Hromatka (12) recently described a new process for conversion of alcohol to acetic acid by submerged fermentation under continued aeration. In the submerged fermentation *Acetobacter* are suspended in alcohol medium in a stainless steel tank provided with aerator and cooler. Very small bubbles of air, such as those formed by Jena 6-4 porous sinter plate, are allowed to pass continually through all of the alcoholic medium, as the bacteria must be in contact with oxygen at all times. If they are deprived of air for more than 15 seconds they are killed. In submerged fermentation pure oxygen or 60% oxygen and 40% nitrogen are harmful. Theoretical yields of acetic acid were obtained and the conversion was more completely controlled than in the generator process. Since the supporting medium occupies a considerable proportion of the space in the usual generator, a much smaller tank can be used in submerged fermentation. This process has not as yet been applied commercially in the U.S., but, in view of the successful application of submerged fermentation in other industrial fermentation processes, it should prove useful.

Vinegar Eels. Vinegar eels (*Anguilla aceti*), which may infest vinegar, are usually considered undesirable and are generally removed from the finished vinegar by pasteurization and filtration. These "eels" are nematodes which are usually about 1/16 in. long. They can be readily observed with a hand lens. Zalkan and Fabian (25), however, have observed that many industrial vinegar generators are infested with these eels with no apparent detriment to the operation. They investigated the effect of vinegar eels on acid production in pilot plant vinegar production and observed higher acetic acid production and greater efficiencies of conversion in generators containing vinegar eels. This effect was particularly evident when the diluted alcohol was fortified with phosphates or with phosphate and nitrate or ammonium chloride. They suggested that the vinegar eels act as scavengers to keep the beechwood shavings free of dead vinegar bacteria and also supply more readily available nutrients to the bacteria.

PREPARATION FOR MARKET

The freshly made vinegar usually is harsh in flavor and odor, not brilliantly clear, and unstable. It is prepared for marketing by aging, and is filtered and clarified, blended and stabilized, and bottled. Vinegar for manufacturing use is shipped in wooden barrels, casks, or tank cars and trucks.

Aging. Cider, wine, malt, and *distilled* vinegar to be bottled for retail distribution as condiment vinegar is pumped from the generator receiving tank into storage containers for aging. During aging and storage the vinegar should be protected against excessive aeration or exposure to air, as this favors growth of acetic acid bacteria, formation of mother of vinegar, and loss of acetic acid by oxidation.

Distilled vinegar, particularly when used for manufacturing, usually is not aged, and is marketed as produced. The generator-produced distilled vinegar may be used as a source of acetic acid (*q.v.*) for industrial use as well as for food vinegar uses. Clean, sound cooperage, treated to prevent absorption of off flavors, is used for storage, which may extend for several weeks or months. Distilled vinegar to be used in manufacture is stored only for clarification treatment. The storage period required to produce a mellow smooth vinegar varies with the source of vinegar stock, the conditions of acetification, and the size and type of storage containers. During storage residual ethyl alcohol is esterified by acetic acid and other organic acids. Other chemical changes, still ill defined, also take place. The storage containers must be kept well filled to avoid oxidation of acetic acid by vinegar bacteria to carbon dioxide and water, which can occur with vinegars of 6% acetic acid content and lower. The final flavor obtained is determined by the type of vinegar stock used and the conditions of acetification and storage. The flavor of distilled vinegar is markedly influenced by the type of denaturant added to distilled high-proof alcohol (1) and the type of water used in diluting the alcohol (1,24). Allgeier *et al.* (1) obtained distilled vinegars of best aroma from denatured alcohol containing specially selected still fractions. The flavor of wine vinegar can be improved by addition of small amounts of aged dry wine. The herb-and-spice-flavored vinegars are carefully compounded and aged to obtain more desirable and more stable flavors.

Filtration and Clarification. The aged vinegars or the freshly prepared vinegars are filtered clear either before or after clarification and metal removal. Cider and particularly wine vinegars usually contain excessive amounts of iron and copper impurities picked up largely from the packing material in the generator (particularly from coke) and from contact with metal surfaces during fermentation and subsequent handling. High iron content will lead to formation of suspended ferric phosphate and ferric tannate colloids and to unsightly deposits of these. High copper content will lead to formation of insoluble copper colloids. The formation of metallic hazes will not occur in absence of proteins and other colloids; they may be removed from vinegar by fining, that is, adding an agent such as bentonite or sodium alginate before filtration. The concentration of iron and copper is reduced by treatment with potassium ferrocyanide (blue-fining) or with specially prepared *adsorption* compounds of potassium ferrocyanide (Cufex is a fining agent prepared from ferrous ferrocyanide, potassium ferrocyanide, citrate, and bentonite). When properly used so that no residual ferrocyanide remains, blue-fining is quite satisfactory. Bentonite and other fining agents may be used either before or after blue-fining. The clarified and metal-stabilized vinegar must be protected against contamination with heavy metals

during the final filtration and filling operations. Filtration is used also in reducing the bacterial population and in removing vinegar eels if present.

Sterilization and Packaging. Pasteurization, addition of small amounts of sulfites, and sterile filtration are used to protect the clarified and filtered vinegar against spoilage by growth of cellulose synthesizing acetic acid bacteria. The temperature and time of pasteurization vary with the extent of infection and conditions of filling. In hot-filling into small containers, the vinegar is brought to 150–160°F., filled hot, sealed, and allowed to cool at air temperature after inversion to sterilize the neck and cap. Vinegar may be pasteurized in bulk by heating to 150°F., holding for 30 minutes, and cooling to 100°F. before filling into large containers. Sulfur dioxide may be used to inhibit growth of vinegar bacteria and also stabilize the vinegar against oxidative deterioration in color and flavor, but the quantities added should be small (usually not over 50 p.p.m.) to avoid effect on aroma and flavor. Contamination with metals (particularly iron and copper) and excessive aeration should be avoided in the final filtration and filling operations. Hard rubber, stainless steel, and glass materials are used in fabrication of pumps, fillers, closing machines, and only chemically inert materials are used in fabricating containers and closures.

Economic Aspects

Very few data on the production and use of vinegar in the U.S. are available. The early data published in the *Census of Manufacture* by the U.S. Bureau of the Census give only the value of the total vinegar produced at the plant and value added in manufacture. The value at the plant was $9,800,000 in 1923, $13,000,000 in 1939, and $33,500,000 in 1947. The annual production of fermented vinegar in 1939 amounted to 61,056,000 gal.; of distilled vinegar, 45,984,000 gal.; and of vinegar stock, cider and semifinished vinegar, 12,618,000 gal. In 1947 there were produced in commercial vinegar plants 39,850,000 gal. of 40 grain fermented vinegar; 40,899,000 gal. of 100 grain distilled vinegar; 7,948,000 gal. of vinegar stock and semifinished vinegar; and 11,629,000 gal. of straight cider.

The U.S. pack of vinegar in glass containers averaged 4.5 million cases during 1941–50, and 5.9 million cases during 1946–50. The largest annual pack during the last decade was in 1944, when 7.0 million cases were packed; in 1951 a little over 6.0 million cases were produced, and this dropped to 5.5 million cases (24 lb. per case) in 1952 and 1953, according to statistical data summarized in the statistical review and yearbook number of *Western Canner and Packer*.

Bibliography

(1) Allgeier, R. J., Wisthoff, R. T., and Hildebrandt, F. M., *Ind. Eng. Chem.*, **44**, 669 (1952); **45**, 489 (1953); **46**, 2023 (1954).
(2) Association of Official Agricultural Chemists, *Official and Tentative Methods of Analysis*, Washington, D.C., 1950, pp. 487-91.
(3) Balcom, R. W., *U.S. Dept. Agr., Bur. Chem. Bull.*, **132**, 96 (1910).
(4) Bitting, A. W., *Fruit Products J.*, **8**, No. 7, 25; No. 8, 16; No. 9, 13; No. 10, 18; No. 11, 16; No. 12, 18; **9**, 19, 25, 59, 86 (1929).
(5) Blair, M. G., and Pigman, W., *Arch. Biochem. and Biophys.*, **42**, 278 (1953).
(6) Brooks, R. O., *Critical Studies in the Legal Chemistry of Foods*, Reinhold, N.Y., 1927.
(7) Cruess, W. V., *Commercial Fruit and Vegetable Products*, McGraw-Hill, N.Y., 1948, pp. 597-617.
(7a) Doro, B., and Sadini, V., *Boll. lab. chim. provinciali (Bologna)*, **4**, 85 (1953).
(8) Foda, I. O., and Vaughn, R. H., *J. Bacteriol.*, **65**, 79 (1953).

(9) Hansen, A. E., *Food Inds.*, 7, 277 (1935).
(10) Herrick, A. D., *Food Regulation and Compliance*, Revere, N.Y., 1944, pp. 177, 178, 218, 427, 428, 431, 433, 441.
(11) Hildebrandt, F. M., *Food Inds.*, **13**, No. 8, 47 (1941).
(12) Hromatka, O., *Chem. Ztg.*, **76**, 776, 815 (1952); *Branntweinwirtschaft*, **6**, 406 (1952).
(13) Hromatka, O., and Ebner, Z., *Enzymologia*, **14**, 96 (1950); **15**, 57, 134, 337 (1951); **18**, 90(1954).
(14) Mitchell, C. A., *Vinegar: Its Manufacture and Examination*, 2nd ed., Griffin, London, 1926.
(15) Prescott, S. C., and Dunn, C. G., *Industrial Microbiology*, McGraw-Hill, N.Y., 1949, pp. 370–87.
(15a) Rainbow, C., and Mitson, G. W., *J. Gen. Microbiol.*, **9**, 371 (1953).
(16) Rao, M. R. R., and Stokes, J. L., *J. Bacteriol.*, **65**, 405 (1953); **66**, 634 (1954).
(16a) Saruno, R., *J. Fermentation Technol. (Japan)*, **32**, 90, 128 (1954).
(17) Saywell, L. G., *Ind. Eng. Chem.*, **26**, 379 (1934).
(18) Shimwell, J. L., *J. Inst. Brewing*, **60**, No. 2, 136 (1954).
(19) Steinmetz, A., *Fruit Products J.*, **14**, 299, 313, 328 (1935).
(20) Tanner, F. W., *The Microbiology of Foods*, Garrard Press, Champaign, Ill., 1944, pp. 723–30.
(21) Tolman, L. M., *J. Assoc. Offic. Agr. Chemists*, **22**, 30 (1939). Hartman, B. G., and Tolman, L. M., *Ind. Eng. Chem.*, **9**, 759 (1917).
(22) *U.S. Dept. Agr., Service and Regulatory Announcements, Food Drug Admin.*, No. **2**, Rev. 4, p. 19 (1933).
(23) Vaughn, R. H., in Underkofler and Hickey, eds., *Industrial Fermentations*, Chemical Publishing Co., N.Y., 1954, Vol. 1, pp. 498–535.
(24) Wüsteinfeld, H., *Lehrbuch der Essigfabrikation*, Parey, Berlin, 1930.
(25) Zalkan, R. C., and Fabian, F. W., *Food Technol.*, **7**, 453 (1953).

M. A. JOSLYN

VINYLACETYLENE, $CH_2{:}CHC{:}CH$. See *Rubber, synthetic*, Vol. **11**, p. 854.

VINYLATION. See *Reppe chemistry*, Vol. **11**, p. 649.

***N*-VINYLCARBAZOLE,** $C_{12}H_8NCH{:}CH_2$. See *Reppe chemistry*, Vol. **11**, p. 656.

VINYL COMPOUNDS, RESINS, AND PLASTICS

Vinyl acetate	p. 686	**Polyvinyl alcohol**	p. 710
Vinyl acetate monomer and other vinyl esters	686	**Polyvinyl acetals**	716
Polyvinyl acetate solid resins	691	**Vinyl chloride**	723
Polyvinyl acetate emulsions	699	**Vinylidene chloride**	736

For vinylation with acetylene and for many other vinyl compounds such as vinyl ethers, see *Reppe chemistry*; for vinylbenzene, see *Styrene*. Acrylic compounds are discussed under *Acrylic and methacrylic acids*; *Acrylic resins and plastics*; and *Acrylonitrile*. See also *Textile fibers (acrylic and vinyl)*, Vol. **13**, p. 824.

VINYL ACETATE

Vinyl Acetate Monomer and Other Vinyl Esters

Vinyl acetate, $CH_2{:}CHOOCCH_3$, formula weight 86.09, is a colorless, mobile, flammable liquid with a characteristic sharp but not unpleasant odor. Its vapor has an irritating effect upon the eyes probably due to its hydrolysis to acetic acid and acetaldehyde.

Vinyl acetate was first mentioned in 1912 by Klatte as a by-product obtained in the preparation of ethylidene diacetate (1,1-ethanediol diacetate, $CH_3CH(OOC-$

$CH_3)_2$) by direct combination of acetic acid and acetylene in the presence of a mercury salt. Substituted vinyl esters had been prepared earlier by Semmler, and Wohl and Mylo, and the latter must have encountered vinyl acetate and failed to recognize it, although they suggest a preparation from α-haloaldehydes.

Vinyl acetate is chiefly used in the preparation of polymers, copolymers, and resins derived from its polymers such as polyvinyl alcohol and the polyvinyl acetals. It also finds some use in the synthesis of drugs and as an acetylating agent.

As of 1954 production in the U.S. (16) and Canada was estimated to be in excess of 100 million pounds per year. The monomer sells for 16–17 cents per pound (19). There is also a substantial production in England, Germany, France, Italy, Switzerland, and Japan.

PROPERTIES

A number of properties of vinyl acetate are given in Table I.

TABLE I. Some Physical Properties of Vinyl Acetate.

Property	Value
B.p., °C.	72–73 (14,17,28)
M.p., °C.	−100.2 (9)
d_{20}^{20}	0.9342 (17), 0.9354 (5)
d_4^{20}	0.9312 (11)
n_D^{20}	1.3956–1.3958 (5,17,28)
Viscosity at 20°C., centipoises	0.432 (17), 0.4213 (28)
Vapor pressure at 20°C., mm. Hg	90 (17), $\log_{10} P_{mm.} = -\frac{0.05223 \times 34433}{T} + 8.091$ (14)
Crit. temp., °C.	228.9 (14)
Crit. pressure, atm.	22.4 (39)
Surface tension at 20°C., dynes/sq.cm.	23.95 (11,21)
Parachor	205 (11)
Dipole moment ($M \times 10^{18}$)	1.75 (13)
Sp. heat (vapor at 1 atm., $p = 1$) (10)	C_p = 22.5 (20°C.); 27.3 (100°C.)
Flash point (Cleveland open cup), °C.	−5 (17), −1 (2)
Autoignition temp., °C.	427 (2,23)
Latent heat of vaporization, kg.-cal./mole	7.8 (17), 8.21 (14)
Heat of formation from acetylene and acetic acid, kg.-cal./mole	ΔH = −28.3 (17)
Heat of combustion, kg.-cal./mole	495 (17)
Heat of polymerization, kg.-cal./mole	21.3 (8,13)

Vinyl acetate is soluble in water to the extent of 2.5 g./100 g. water at 20°C. (17) and 2.1 g./100 g. water at 50°C. (20). Water is soluble in vinyl acetate to the extent of 0.1 g./100 g. vinyl acetate at 20°C. and 1.7 g./100 g. vinyl acetate at 66°C. The equilibrium diagram of solubility for the system vinyl acetate–acetic acid–water is given in reference (25) and for the system vinyl acetate–acetone–water in reference (26). The boiling point of the constant-boiling mixture of vinyl acetate and water (93.5% by weight of vinyl acetate) is 66°C.; of vinyl acetate and toluene (96% by weight of vinyl acetate) is 72.6°C.; and of vinyl acetate and methanol (60% by weight of vinyl acetate) is 59.3°C.

The ultraviolet (7) and infrared (1,3) absorption spectra and the Raman spectrum (30) for vinyl acetate have been determined.

LD_{50} of vinyl acetate for rats is 0.3 g./kg. (27).

REACTIONS

The most important reaction of vinyl acetate is its ready polymerization in the presence of peroxide or other catalysts, although it shows little tendency to polymerize in the absence of catalysts and light. By this reaction it is the parent of polyvinyl acetate, polyvinyl alcohol, and polyvinyl acetals.

Vinyl acetate is hydrolyzed with dilute acid or alkali yielding acetic acid (or the corresponding salt when alkali is used) and acetaldehyde. The rate of hydrolysis, K, as calculated from $\log 1/(1 - x) = 2.3Kt$, where x is the fraction of vinyl acetate hydrolyzed and t is the time in minutes, is 0.3 at 25°C., 2.3 at 60°C., and 7.8 at 80°C. Monomeric vinyl alcohol, the enol of acetaldehyde (*q.v.*), which might have been expected as one of the products of hydrolysis, has never been isolated.

The ease with which vinyl acetate yields acetic acid and the volatility of acetaldehyde make vinyl acetate a convenient acetylating agent for alcohols, for example *n*-butyl acetate is readily prepared by heating a mixture of vinyl acetate (containing a cupric salt as polymerization inhibitor), and *n*-butyl alcohol with traces of sulfuric acid and continuously removing the acetaldehyde by means of an efficient column (24).

Chlorine or bromine adds readily to give the 1,2-dihaloethyl acetate, which can be distilled under reduced pressure without decomposition. Hydrogen chloride or hydrogen bromide adds readily and quantitatively at low temperatures to give the 1-haloethyl acetate (17).

Ozone reacts readily yielding ozonides which are very explosive when dry (17).

Vinyl acetate is said to condense with acetaldehyde (15) forming acetals; with phenol to give *o*-vinylphenol (4), or at a high temperature phenyl acetate (13). On warming with acetic acid in the presence of sulfuric acid ethylidene diacetate is formed, which at higher temperatures decomposes to yield acetic anhydride and acetaldehyde.

Vinyl acetate may be used for preparation of higher-boiling vinyl esters by means of an interchange reaction if treated with the acid of the desired ester and the mercuric salt of a strong acid (1).

MANUFACTURE

Liquid Phase (17). This older commercial process is by the reaction of acetylene with acetic acid at about 80°C. in the presence of mercury salts of sulfuric or acetyl sulfuric acid. By using a large excess of acetylene the vinyl acetate is removed as fast as it is formed and recovered by condensation. The excess acetylene is recycled, and the vinyl acetate purified by distillation.

Vapor Phase. This process (32) has almost replaced the older process of manufacture. Gaseous acetic acid and acetylene are passed through charcoal impregnated with cadmium or zinc salts in a reactor held at around 200°C. A large excess of acetylene is used.

Corrosion-resistant iron or stainless steel are preferred for the construction of all apparatus. Copper may be used up to the vapor line in stills, but beyond this point it must be replaced by stainless steel. Storage tanks may be stainless steel, aluminum, or steel.

Many other vinyl esters have been made by this process and their properties studied (see Table II). Very few have found any commercial use by themselves. Vinyl formate polymerizes readily, yielding a resin somewhat like polyvinyl acetate but which proved to be too readily hydrolyzed in water. Vinyl monochloroacetate

found a small market in Germany in the form of its polymer (Mowilith G) but few of its properties were superior to those of the cheaper polyvinyl acetate. Vinyl crotonate and vinyl benzoate have been described in German literature but do not appear to be available in commercial quantities in North America. Vinyl stearate is being manufactured in small quantities in the U.S., its chief use being in the preparation of vinyl acetate copolymers.

TABLE II. Miscellaneous Vinyl Esters.

Ester	B.p., °C.	Refractive index, n_D^{20}	Sp.gr.
Vinyl abietate	$200\text{-}225_{6\text{-}7}$ (34,36,37)	—	1.037_4^{20} (6)
	236_{16} (6)	1.5378 (6)	
Divinyl adipate	118_8 (1)		
Vinyl acetylsalicylate	148_3 (34,36,37)		
Vinyl acrylate	94 (41)		
Vinyl benzoate	80_{12}; $100\text{-}101_{25}$ (1)	$1.5259_D^{21.5}$ (1)	1.0706_{20}^{20}
Vinyl butyrate	116.5	1.411	0.8994_{20}^{20}
Vinyl campholate	$78\text{-}79_7$ (39)		
Vinyl caproate	166 (34,36,37)		
Vinyl caprylate	94_{12} 135_{60}	$1.4271_D^{22.5}$	0.8719_4^{20}
Vinyl *o*-chlorobenzoate	115_{12} (12), m.p. −21	1.5440_D^{25}	
Vinyl *p*-chlorobenzoate	122_{20} (12), m.p. +49.5		
Vinyl crotonate	133	1.450	0.9410_4^{20}
	45_{12}		
	$25_{9.5}$		
Vinyl diethylacetate	147 (22)		
Vinyl formate	44		
Vinyl isobutyrate	101		
Vinyl lactate	$50\text{-}60_{25}$		
Vinyl laurate	123_4 (34,36,37)	$1.4386_D^{21.5}$ (1)	0.8770^{28} (1)
Vinyl linoleate	$170\text{-}200_6$ (34,36,37)		
Vinyl methoxyacetate	38_{12} (38)		
Vinyl methacrylate	117_{15} (40)		
Vinyl *p*-methoxybenzoate	140_{30} (12), m.p. 58		
Vinyl monochloroacetate	135	1.4445	1.190_{20}^{20}
Vinyl myricate	150_3 (34,36,37)		
1-Vinyl naphthoate	150_5 (34,36,37)		
2-Vinyl naphthoate	153_4 (34,36,37)		
Vinyl octyl phthalate	$138\text{-}142_{0.01}$	1.4979_D	1.01^{20}
Vinyl oleate	173_2 (34,36,37)	1.4533 (1)	0.8691_4^{30} (29)
Vinyl palmitate	165_2 (34,36,37)		
Vinyl phenylacetate	$88\text{-}90_4$ (34,36,37)		
Vinyl *p*-phenylbenzoate	$169_{3.5}$ (12), m.p. 51		
Vinyl propionate	95		
Vinyl salicylate	$97\text{-}98_1$ (18), m.p. 32–33 (18)	1.5398_D^{25} (18)	
Vinyl stearate	167_2, m.p. 30–32 (1)	1.4423_D^{30}	0.8517^{40} (1)
Vinyl trimethylacetate	109_{748} (22)	1.4068 (1)	0.885^{20} (1)
Vinyl 3,5,5-trimethylhexanoate	$85\text{-}95_{20\text{-}26}$	$1.4226_D^{21.5}$ (1)	
Vinyl thiolacetate	121 (35)	1.4892	1.0136_{25}^{25}
Vinyl *m*-toluate	102_{11} (12)	1.5246	
Vinyl *p*-toluate	$103_{11.5}$ (12)	1.5268	
Vinyl valerate	134 (1,34,36,37)		

Stabilization. During refining, shipping, and storage, polymerization inhibitors are added as stabilizers. Usually these must be removed by distillation before use,

but large shipments are made in which the stabilizer is present in amounts that do not require removal for polymerization reactions. The most common stabilizers are: copper acetate, copper resinate, diphenylamine, hydroquinone, or sulfur. The amount used varies between 0.01% and 0.5% based on the weight of vinyl acetate.

Shipping Instructions. Vinyl acetate, being a flammable volatile liquid, comes under the Interstate Commerce Commission Tariff #9. This calls for steel drums with a "red label" (keep from fire) or steel tanks with "dangerous" placards. All shipments are stabilized. Special regulations may apply for shipments through tropical zones.

ANALYSIS

The per cent *vinyl acetate* in a sample is determined by adding bromine water to the sample in an acetic acid–water solution until a slight yellow color persists. The excess bromine is titrated by adding potassium iodide, and determining the liberated iodine with 0.1 *N* thiosulfate. A blank on the bromine water is run at the same time.

The per cent *acid* in a vinyl acetate sample is determined by titrating the free acid in an ice-cold aqueous solution of the sample. The *acetaldehyde* content is determined by adding sufficient 0.1 *N* iodine solution to water containing starch indicator to develop a blue color. A small amount of approximately 1 *N* sodium bisulfite is added followed by an aliquot of the vinyl acetate. After shaking and standing for a short period of time, the excess bisulfite is titrated with 0.1 *N* iodine solution. A blank on the bisulfite should be made at the same time as the analysis. *Water* is determined by the Karl Fischer reagent (24).

Bibliography for Vinyl Acetate Monomer

(1) Adelman, R. L., *J. Org. Chem.*, **14**, 1057 (1949).
(2) Associated Factory Mutual Fire Insurance Companies, *Ind. Eng. Chem.*, **32**, 880 (1940).
(3) Barnes, R. B., Liddel, U., and Williams, V. Z., *Anal. Chem.*, **15**, 689 (1943).
(4) Blout, E. R., and Mark, H., *Monomers*, Interscience, N.Y., 1951.
(5) Breitenbach, J. W., and Raff, R., *Ber.*, **69B**, 1107 (1936); *C.A.* **30**, 5181.
(6) Brus, G., Thoi, L.-V., Fargeaudoux, S., *Industrie plastiques mod.* (*Paris*), **5**, No. 8, 51, 53 (1953); *C.A.*, **48**, 3719.
(7) Calvin, M., Magel, T. T., and Hurd, C. D., *J. Am. Chem. Soc.*, **63**, 2175 (1941).
(5) Dainton, F. S., and Ivin, K. J., *Trans. Faraday Soc.*, **46**, 331 (1950).
(9) Dolliver, M. A., Gresham, T. L., Kistiakowsky, G. B., Smith, E. A., and Vaughan, W. E., *J. Am. Chem. Soc.*, **60**, 440 (1938).
(10) Fugassi, P., and Rudy, C. E., Jr., *Ind. Eng. Chem.*, **30**, 1029 (1938).
(11) Green, C., Marsden, J., and Cuthbertson, A. C., *Can. J. Research*, **9**, 396 (1933).
(12) Ham, G. E., and Ringwald, E. L., *J. Polymer Sci.*, **8**, 91 (1952).
(13) Lee, S., *J. Soc. Chem. Ind. Japan*, **43**, Suppl. 190 (1940) (in German); *C.A.*, **34**, 7677.
(14) Marsden, J., and Cuthbertson, A. C., *Can. J. Research*, **9**, 419 (1933).
(15) Marvel, C. S., Harmon, J., and Riddle, E. H., *J. Org. Chem.*, **4**, 252 (1939).
(16) *Modern Plastics*, **31**, 103 (1953).
(17) Morrison, G. O., and Shaw, T. P. G., *Trans. Electrochem. Soc.*, **63**, 425 (1933).
(18) Mowry, D. T., Yanko, W. H., and Ringwald, E. L., *J. Am. Chem. Soc.*, **69**, 2358 (1947).
(19) *Oil, Paint, Drug Reptr.*, **165**, No. 26, 30 (1954).
(20) Okamura, S., Torii, K., Oshima, Y., Toyama, E., and Yoshikawa, S., *J. Soc. Chem. Ind. Japan*, **49**, 20 (1946); *C.A.*, **42**, 6575 (1948).
(21) Quayle, O. R., *Chem. Revs.*, **53**, 522 (1953).
(22) Schildknecht, C. E., *Vinyl and Related Polymers*, Wiley, N.Y., 1952, p. 378.
(23) Scott, G. S., Jones, G. W., and Scott, F. E., *Anal. Chem.*, **20**, 238 (1948).
(24) Smith, D. M., Bryant, W. M. D., and Mitchell, J., Jr., *J. Am.Chem. Soc.*, **61**, 2407 (1939).

(25) Smith, J. C., *J. Phys. Chem.*, **45**, 1301 (1941).
(26) Smith, J. C., *J. Phys. Chem.*, **46**, 229 (1942).
(27) Smyth, H. F., Jr., and Carpenter, C. P., *J. Ind. Hyg. Toxicol.*, **30**, 63 (1948); *C.A.*, **42**, 1677.
(28) Staudinger, H., and Schwalbach, A., *Ann.*, **488**, 8–56 (1931); *C.A.*, **25**, 5138 (1931).
(29) Swern, D., Billen, G. N., and Knight, H. B., *J. Am. Chem. Soc.*, **69**, 2439 (1947).
(30) Taufen, H. J., and Murray, M. J., *J. Am. Chem. Soc.*, **67**, 754 (1945).
(31) Tong, L. K. J., and Kenyon, W. O., *J. Am. Chem. Soc.*, **69**, 2245 (1947).
(32) Ushakov, S. N., and Feinstein, J. M., *Ind. Eng. Chem.*, **26**, 561 (1934).
(33) Brit. Pat. 314,646 (May 14, 1928), W. O. Herrmann and H. Deutsch (to Consort. f. elek. Ind.).
(34) Brit. Pat. 395,478 (July 20, 1933), I. G. Farbenind.
(35) Brit. Pat. 568,565 (April 11, 1945), M. M. Brubaker (to Du Pont).
(36) Ger. Pat. 588,352 (Nov. 15, 1933), W. Reppe (to I. G. Farbenind.).
(37) Ger. Pat. 589,970 (Dec. 20, 1933), W. Reppe (to I. G. Farbenind.).
(38) U.S. Pat. 2,021,873 (Nov. 19, 1935), O. Nicodemus and W. Weibezahn (to I. G. Farbenind.).
(39) U.S. Pat. 2,310,780 (Feb. 9, 1943), W. E. Hanford and W. E. Mochel (to Du Pont).
(40) U.S. Pat. 2,344,798 (March 21, 1944), J. H. Brown and J. S. Watt (to Imperial Chemical Industries Ltd.).
(41) U.S. Pat. 2,363,286 (Nov. 21, 1944), W. Bauer and C. T. Kautter (to Röhm and Haas Co.).

T. P. G. SHAW

Polyvinyl Acetate Solid Resins

The polymerization of vinyl acetate, $CH_3COOCH{=}CH_2$, to a solid resinous body was first mentioned by Klatte and Rollett (30,31) in 1913. Little interest was shown, aside from some fundamental studies by Staudinger and his students (25), until a serious attempt at commercial development of the polymer was started by Shawinigan Chemicals Ltd. in Canada in 1925. Commercial production began in 1929 and by 1953 had reached between 75 and 95 million pounds in the U.S. (17), including that used in the production of polyvinyl acetals, polyvinyl alcohol, and emulsions. Production in Europe, Canada, and Japan would probably equal this figure.

PROPERTIES

The structure of these polymers is best represented by:

$$\left[\begin{array}{l}-CH_2-CH- \\ \quad\quad\quad | \\ \quad CH_3COO\end{array}\right]_n$$

The polymers vary with increasing values of n from viscous liquids through low-melting solids to tough horny materials. They are neutral, water-white to straw-colored, tasteless, odorless, and nontoxic.

The resins are graded by the viscosity in centipoises of a solution of 86 g. resin made up to 1 liter with benzene and measured at 20°C. This designation is generally used in North America. In Europe, the Fikentscher "K" value is in more common use. The relationship is shown below:

Fikentscher "K" value.....	20	30	40	50	60	70	80	90
Grade viscosity.....	2.6	5.8	12.5	28.5	78	225	880	4000

The resins have no sharply defined melting point but become softer as the temperature is raised. The standard grades with a softening point determined by the K.&S. (1)

or ring and ball (2) method and the molecular weight by the osmotic method are given in Table I.

TABLE I. Softening Points and Molecular Weights of Commercial Polyvinyl Acetates.

Grade viscosity	Softening point, °C.		Approximate molecular weight
	K.&S.	R.&B.	
1.5	65	75	10,000
2.5	81	90	15,000
7	106	116	33,000
15	131	139	60,000
25	153	163	100,000
45	180	—	135,000
60	196	—	155,000
145	—	—	225,000
500–1000	—	—	400,000–600,000

Many of the physical properties of the polyvinyl acetates are almost independent of the viscosity grade and, unless otherwise noted, this is true of those given in Table II.

TABLE II. Physical Properties of Polyvinyl Acetates.

Property	Value
Density	
At 20°C.	1.19
At 60	1.16
At 120	1.11
At 200	1.05
n_D^{20}	1.467
n_D^{80}	1.448
Water absorption (A.S.T.M. 48-hr. test), %	2
Transition temp. (second-order), °C.	30–34 (15)
Tensile strength, p.s.i.	5,000
Thermal coefficient of linear expansion, per °C.	8.6×10^{-5} (7)
Thermal conductivity, cal./(sec.)(sq. cm.)(°C./cm.)	38×10^{-5}
Sp. heat	0.389
Heat distortion point °C.	50
Burning rate	Very slow
Dielectric strength, volts/mil	
At 30°C.	1,000
At 60	780
Dipole moment, Debye units	1.85 (8)

Electrical properties (18)

	Frequency	Dielectric constant	Power factor
At 30°C.	60 cycles	3	0.01–0.02
At 60	60 cycles	6	0.07
At 20	1 kc.	3.15	0.025
	100 kc.	3.09	0.028
	1 Mgc.	3.06	0.03
	10 Mgc.	3.02	0.025

Solvents that will dissolve 20% or more of their weight of resin at room temperature are: acetic acid or anhydride, benzyl alcohol, diacetone alcohol, 95% ethyl alco-

hol, methanol, acetaldehyde, paraldehyde, furfural, aniline, pyridine, carbon tetrachloride, chlorobenzene, chloroform, dichloroethylene, trichloroethylene, *n*-butyl acetate, ethyl acetate, isopropyl acetate, Cellosolve, dioxane, methyl Cellosolve, benzene, toluene, acetone, methyl ethyl ketone, nitrobenzene, nitromethane, liquid sulfur dioxide, and pine oil.

Nonsolvents are: aliphatic hydrocarbons, fats, waxes, glycols, turpentine, xylene, water, ether, carbon disulfide, and glycerol. 1-Butanol and xylene are solvents at higher temperatures.

Tack temperatures are (14): grade 7, 49°C.; grade 15, 63°; grade 25, 66°.

The permeability to saturated water vapor at 40°C. is 0.021 g./hr./100 sq. cm. per mil of film thickness; to hydrogen (22), 3–13 l./24 hr./sq. m. at 1 atm. pressure.

Polyvinyl acetates are compatible with Aroclors; many Bakelite BR and XR resins; Beckacite 1001 and 1003; Bola-Bold; dewaxed dammar; elemi; Hercose AP or C; Nevillac; Neville R-27; Nevindene R-17; nitrocellulose; some Rezyls, rosin; Santolite K, MHP, and MS; Vinsol; and yucca when dissolved in mutual solvents.

Plasticizers may be incorporated in solution or by hot mixing on roll mills. A few of the most effective plasticizers are dibutyl phthalate; Flexol 3GO, 4GO, or 3GH; Santicizer B16, M17, and E15; and Thiokol TP9OB. They are used to increase the flexibility of the compound, reduce its softening point, or increase the tackiness.

The adhesion of polyvinyl acetate to wood, glass, and various metals is in the order of 1,000–1,700 p.s.i. at 25°C. (23). The abrasion resistance and scratch hardness are about twice those of a film from oleoresinous clear varnishes (23).

Stability. Polyvinyl acetate resins are unaffected by sunlight or air. Ultraviolet light quickly produces a slight surface change which renders the film opaque to wave lengths below 3200 A. The polymer shows no visible discoloration.

When heated above room temperature all viscosity grades become very flexible and limp at 50°C. They will stand hours of heating at 125°C. without change, but at 150°C. will gradually darken in color, and at over 225°C. will liberate acetic acid forming a brown insoluble resin which in turn will carbonize at a much higher temperature. On cooling below room temperature, polyvinyl acetates all become brittle at 10–15°C. The brittle point may be lowered somewhat by plastification.

Ageing qualities are excellent due to its resistance to oxidation and inertness to the effects of ultraviolet light.

Reactions. Being polyesters, these resins are easily saponified or hydrolyzed in alcoholic solution to polyvinyl alcohol (24). The polymers are quite resistant to dilute alkali (aqueous), acids, or salts; chlorine, sulfur dioxide, or hydrogen sulfide gases (20).

Concentrated hydrochloric acid dissolves the polymers at ordinary temperatures causing hydrolysis to polyvinyl alcohol and acetic acid. This is the basis for a process for manufacture of polyvinyl formal (29). Concentrated sulfuric acid causes charring, and concentrated nitric acid oxidizes it to oxalic acid and other products with the evolution of nitric oxide.

MANUFACTURE

The preparation of polyvinyl acetate and its manufacture may be divided into three main types of process: bulk, solution, and bead polymerization of the monomer.

Generally, the polymerization is a typical free radical chain reaction yielding macromolecules. The reaction is catalyzed by peroxides or light of definite wave lengths (for example, mercury arc). Although the polymers are essentially straight chains, a small amount of branching between chains does occur (3,24). This is more pronounced with the higher-molecular-weight polymers and in the bead process for polymerization. The breakdown of these crosslinkages is the reason why the reacetylation of a polyvinyl alcohol gives a lower-grade viscosity polyvinyl acetate than the original polyvinyl acetate from which it was made (3). It is also the cause of the small amount of insoluble, gelled particles often found in polyvinyl acetate solutions.

Bulk Polymerization. In bulk polymerizations using a batch process only small amounts of monomer may be safely handled. If carried out under nitrogen in light at room temperature the reaction is slow. If the polymerization is initiated by peroxides the reaction may reach almost explosive violence. The degree of polymerization may be controlled by additions of chain terminators such as acetaldehyde.

A continuous polymerization process used commercially in Germany is fully described by Dunlop and Reese (9). The process was suitable for only the lowest-viscosity grades and gave trouble due to fouling of the apparatus with high viscosity or insoluble resin.

Solution Polymerization. A mixture of vinyl acetate (60 volumes) and benzene (40 volumes) or other solvent is fed to a jacketed stirred kettle fitted with a reflux condenser. About 0.2% (on the vinyl acetate) of a peroxide catalyst (benzoyl peroxide, lauroyl peroxide, or acetyl peroxide in solution in benzene or vinyl acetate) is added, and the temperature is raised until a gentle reflux is obtained. After 3 hours, about 70% of the vinyl acetate will have polymerized and the run is transferred to another kettle where the solvent and unreacted vinyl acetate are recovered by steam distillation at 60–80 lb. pressure. The wet polymer, which contains about 15% water, is dried. For drying, the lower viscosity grades (1.5–7) may be run on to trays and dried in a vacuum tray dryer. The higher grades may be extruded into rods (19), which are cut into flakes and dried at 50 °C. in warm air, crushed, blended for uniformity of grade, and packed in fiber drums, or multiwall paper bags.

Dunlop and Reese describe a German continuous process in some detail which is said to operate satisfactorily (9).

The molecular weight of the polymer obtained is dependent on a number of factors (3,24), for example, concentration of the monomer, temperature, type of solvent, concentration of catalyst, type of catalyst, and the addition of various chain transfer agents to stop the growth of individual chains. For production of a given viscosity grade exact control of these factors is necessary.

Bead Polymerization. Vinyl acetate may be polymerized in aqueous dispersion to give a product in the form of beads or pearls, the size of which is subject to control. This process has the advantage over solution polymerization of easy temperature control and absence of expensive solvents. Very high-molecular-weight polymers can be obtained and virtually complete polymerization of the monomer is possible. However because of a greater tendency to branching and eventual cross linking of the chains in this process, it is often preferable to stop the polymerization at 70–80%. This process differs from the emulsion process chiefly in the size of the particles produced. The larger particles are obtained by using a much smaller amount of protective colloid and carefully balancing the proportion of colloid and wetting agent.

A typical run (10) is made by charging 800 parts by weight of water and 0.8

part dispersing agent (polystyrene–maleic acid copolymer sodium salt) to the jacketed, stirred reactor. The temperature is raised to 80°C., then 600 parts monomer with 5.4 parts benzoyl peroxide and 3 parts ethyl acetate are added in about 1½ hours. After about half the monomer has been added, the reaction becomes quite vigorous and the run must be cooled to hold the temperature at 80°C. The monomer rate is controlled so that there is a gradual rise to 85°C. as the last of the monomer is added. The temperature is finally raised to 93°C., then the kettle is vented and blown with air to remove any unreacted monomer. The batch is discharged to a cooling vessel, where it is cooled, using first water then brine on the jacket, to 4°C., centrifuged, washed with water at 5°C., and dried in a tray dryer for 40 hours at 25–30°C. This procedure produces a resin of about 25-grade viscosity.

The size of bead produced depends on speed of stirring, nature and amount of dispersing agent, proportion of wetting agent if any is used, temperature of reaction (35), and monomer-water ratio. Polyvinyl alcohol–acetate (20% acetate content) is commonly used as the dispersing agent, although hydroxyethyl cellulose and carboxymethyl cellulose have been employed. Sticking together of the beads on drying is prevented by a thin coating of glyceryl monostearate (Darvan 1), waxes, or calcium stearate.

The equipment for reactors and piping may be aluminum, although most manufacturers prefer glass-lined polymerization kettles because less fouling with insoluble polymer is encountered. Copper should be used for storing wet solvent–vinyl acetate mixtures, but dry solvent mixtures may be stored in iron or aluminum.

Methods of Analysis. *Viscosity.* The sample is dried at 100°C. for 1 hour, then 8.6 g. of resin is dissolved in benzene and made up to 100 ml. The viscosity in centipoises at 20°C. is determined in an Ostwald viscometer.

Moisture Content. This may be determined by dissolving a weighed sample in dry methanol and determining the water content by the Karl Fischer method (12). Water may also be determined using A.S.T.M. D95 apparatus by distilling the water from a 25-g. sample of resin with toluene.

Insolubles. A 50-g. sample is placed in a thimble made of 60-mesh screen and submerged in ethyl acetate at room temperature for 24 hours. It is then removed and washed in fresh ethyl acetate for 1 hour, dried at 105°C., and weighed. The gain in weight of the thimble is calculated to per cent as insolubles.

Specifications, Trade names. The resins are supplied either in solution in suitable organic solvents or as solids. The solids may be in the form of beads, granules, or, in the lower grades, large blocks. They are packed in fiber drums or multiwall paper bags, which should be stored in a cool place to prevent caking of the product. Typical specifications are:

Acidity as acetic acid	Less than 0.1%
Viscosity	Normal grade ± 10%
Moisture	Less than 2.25%
Color	Water-white to pale-straw
Insolubles (not for bead types)	Less than 0.3%

They are supplied in North America under the following trade names (most of the companies supply a number of different viscosity grades): Bakelite vinyl acetate resins (Bakelite Co.), Beech-Nut resins (Beech-Nut Packing Co.), Elvacet (Du Pont), Gelva (Shawinigan Chemicals Ltd. and Shawinigan Resins Corp.), Lemac and Polyco

(Borden Co.), Resyn (National Starch Products, Inc.), Vinac and Vinacol (Colton Chemical Co.).

In Europe there are the following trade names: Mowilith (Farbwerke Hoechst AG), Novyl and Novylol (Société Nobel Française), Rhodopas (Société des usines chimiques Rhône-Poulenc), Texilac (Scott Bader and Co. Ltd.), Vinalak (Vinyl Products Ltd.), Vinavil (Rhodiatoce S.p.A.), Vinnapas (Wacker-Chemie GMBH), Vipol (Lonza).

USES

Polyvinyl acetate is used largely in adhesives and the manufacture of polyvinyl acetals (*q.v.*) and polyvinyl alcohol (*q.v.*), but it also finds some applications in molding of records and filled objects or ornaments, lacquers, lamination of textiles, preservation of fruit and eggs, and surgical dressings.

Adhesives. *Solution adhesives* for labels on textiles may be made according to the following recipe:

Acetone	56.3 U.S. gal.
Di-*n*-butyl phthalate	0.95 U.S. gal.
Viscosity grade 15 polymer	450 lb.

Hot-melt adhesives eliminate the use of solvents and have many advantages over solutions in bonding speed and cost. They are applied in the molten condition and may be bonded while in this state or by remelting at a later time. These adhesives are much used for laminating metal foils to paper. A formula suitable for use with cellophane, paper, or aluminum foil consists of:

Di-*n*-butyl phthalate	10 lb.
Rosin	12 lb.
Viscosity grade 7 polymer	78 lb.

This is mixed at 150°C. and may be applied at 125°C.

Tape or Film. Polyvinyl acetate film may be formed by drawing a suitably plasticized melt of viscosity grade 15 polymer to the proper thickness. The film is quickly cooled, slit, and rolled with paper between the layers of resin. Such tape is largely used for joining breaks in paper in mills and printing plants. A similar film is used for mounting photographs and generally as a heat-sealable adhesive film.

Coatings (see Vol. 4, p. 180). Low-viscosity polymers may be compounded with Santolite resins (Monsanto Chemical Co.) and stearic acid for use in the molten condition for greaseproofing and raising the transparency of paper. Higher-viscosity polymers must be used in solution for this purpose.

High polymers are used in treating the liners in starchless collars. These collars are made with a coarse liner coated with polyvinyl acetate solution and dried. This liner is laminated by ironing to the outer fine fabric (broadcloth). On laundering, the bond between the fine fabric and the liner breaks, permitting easy removal of dirt from the fine fabric. The bond is restored by ironing.

Lacquers form a special class of coatings where the clarity and color stability of these resins makes them useful for decorative coatings, silver lacquers, and temporary finishes for the protection of copper or chrome doorways, etc., from plaster droppings during building construction. A lacquer coating strengthens a plaster mold and gives a better surface to the molding. The solutions make good carriers for metallic pigments. Clear lacquers have been recommended for the preservation of museum

artifacts (13), and are used in finishing straw hats because of their nonyellowing property.

Fruit, vegetables, and eggs are preserved by coating with alcoholic polyvinyl acetate solutions. These resins are particularly suitable for surgical and medicinal preparations (26), x-ray shields, and plastic dressings. Coatings are also applied to flash bulbs to prevent the glass shattering.

Molding. Because of the tendency for these resins to warp or show cold flow at moderate temperatures, they are mixed with fibrous materials and other resins to improve their form stability. Novelties, trays, and phonograph records can be molded by compression or extrusion of such compounds.

A formulation (23) used for extruded objects is:

Viscosity grade 25 polyvinyl acetate	64 parts
Yucca (accroides)	32 parts
Carnauba wax	4 parts

Fine wood meal and/or cotton flock are mixed in to give the desired effect.

Plastic wood may be considered a special type of molding compound applied by hand-forming; several formulations are given by Sohngen (32).

Chewing Gum Base. The largest proportion of the very low-viscosity grade polymers is used in chewing gums (see Vol. **7,** p. 338). Suitable bases are complex mixtures and are covered by patents (34).

Miscellaneous. These include printing inks, stiffeners for box toes for shoes, binders for asbestos paper, balloon fabrics, milk bottles and other food packages. At one time there was a craze for the blowing of balloons from a concentrated polyvinyl acetate solution (16).

VINYL ACETATE COPOLYMERS

In an effort to improve some of the poorer properties of polyvinyl acetate (such as its low heat distortion point, high brittle point, and water absorption), copolymerization of vinyl acetate with many other monomers has been tried. Bulk, solution, bead, or emulsion polymerization may be used. (For the copolymers of vinyl acetate with vinyl chloride where the latter is the major constituent, see "Vinyl chloride," p. 723.)

A copolymer 70% vinyl acetate with 30% vinyl chloride sold in Germany (Appretan) shows greatly improved water absorption and resistance to hydrolysis. This is used in paints for exterior work (4,5). Another commercial copolymer of 85% vinyl acetate with 15% vinyl benzoate, sold in Germany as Mowilith AB, is used as a water repellent for wrapping paper (5).

Vinyl acetate copolymerized with 1–5% crotonic acid (5,11,33) gives a product soluble in dilute ammonia or sodium carbonate aqueous solutions. It is used for textile sizes, stiffening of felts, and adhesives (Appretan H, Mowilith CT-5).

With maleic anhydride in equimolar proportions, the copolymer is also alkali-soluble and forms clear lacquer films from water which with plasticizers are relatively water-resistant (11). The polymerization of vinyl acetate with diethyl (or dimethyl) maleate followed by complete hydrolysis results in a crosslinked polyvinyl alcohol (11). Compounds of this type have potential uses as soil conditioners (6). See Vol. **12,** p. 631.

Internally plasticized polymers are made using 70 parts vinyl acetate, 30 parts *n*-butyl acrylate, or larger amounts of the lower acrylate esters (11,21). These show

higher and wider softening ranges and increased rubberiness. On controlled hydrolysis, they yield a lactone structure which is swollen but insoluble in water while remaining soluble in organic solvents.

Ethylene–vinyl acetate copolymers have been the subject of a number of patents issued to Du Pont with claims that partial hydrolysis yields products insoluble in hot or cold water, with good low-temperature flexibility and toughness (27,28). These copolymers are said to have uses in adhesives coatings, films, and fabrics but do not appear to have reached the commercial stage yet.

Although many other monomers may be copolymerized with vinyl acetate, no commercially useful products seem to have been obtained. Some monomers inhibit the polymerization of the vinyl acetate or may copolymerize only in very limited ranges. In some cases where a monomer will not copolymerize with vinyl acetate, addition of a third monomer makes a ternary polymer possible. Thus, styrene and vinyl acetate may be copolymerized in the presence of acrylate esters.

Bibliography for Polyvinyl Acetate Solid Resins

(1) Abraham, H., *Asphalts and Allied Substances*, 5th ed., Van Nostrand, N.Y., 1945.
(2) *A.S.T.M. Standards on Petroleum Products and Lubricants*, Committee D-2, Nov. 1949, p. 1281.
(3) Blaikie, K. G., and Crozier, R. N., *Ind. Eng. Chem.*, **28**, 1155–9 (1936).
(4) *British Intelligence Objectives Subcommittee, Final Rept.*, No. **744**, Item 22.
(5) Boundy, R. H., and Hasche, R. L., *Office Tech. Services Rept.* **PB-23741**, June 12, 1945.
(6) *Chem. Week*, **74**, No. 3, 62 (1954).
(7) Clash, R. F., Jr., and Rynkiewicz, L. M., *Ind. Eng. Chem.*, **36**, 279–82 (1944).
(8) Dakin, T. W., *Trans. Electrochem. Soc.*, **83**, 175–85 (1943).
(9) Dunlop, R. D., and Reese, F. E., *Ind. Eng. Chem.*, **40**, 654–60 (1948).
(10) *F.I.A.T.*, No. **1102**, April 22, 1947, p. 10.
(11) *F.I.A.T.*, No. **1166**, May 1947.
(12) Fischer, K., *Angew. Chem.*, **48**, 394–96 (1935).
(13) Gettens, R. J., *Tech. Studies Field Fine Arts*, **4**, 15–27 (1935).
(14) McLaren, A. D., Li, T. T., Rager, R., and Mark, H., *J. Polymer Sci.*, **7**, 463–71 (1951).
(15) Meissner, H. P., and Merrill, E. W., *Modern Plastics*, **26**, No. 8, 104, 106, 108, 158, 160, 162, 166 (1949).
(16) *Modern Plastics*, **25**, No. 2, 110 (1947).
(17) *Modern Plastics*, **31**, No. 1, 103 (1953).
(18) Morgan, S. O., and Yager, W. A., *Ind. Eng. Chem.*, **32**, 1528 (1940).
(19) Mueller, W. H., *Can. Chem. Process Inds.*, **29**, 395–97 (1945).
(20) Ohl, F., *Farbe u. Lack*, **1935**, 195–96, 206–7, 221, 231–32; *C.A.*, **29**, 4957 (1935).
(21) Rohm & Haas, *Copolymerization of Acrylic Esters* (SP 147), Philadelphia, Pa., April 1954.
(22) Sager, T. P., *J. Research Natl. Bur. Standards*, **13**, 884 (1934).
(23) Shawinigan Chemicals Ltd., unpublished data.
(24) Skirrow, F. W., *British Plastics*, **10**, 416, 419, 507–10 (1939); *Chemistry & Industry*, **57**, 1117–23 (1938).
(25) Staudinger, H., Frey, K., and Starck, W., *Ber.*, **60B**, 1782–92 (1927).
(26) Brit. Pat. 554,295–6 (June 28, 1943), D. W. Burley and H. J. Stern (to T. J. Smith and Nephew Ltd.).
(27) Brit. Pat. 585,969 (March 3, 1947) (to Du Pont).
(28) Brit. Pat. 607,911 (Sept. 7, 1948) (to Du Pont).
(29) Fr. Pat. 750,350 (Aug. 8, 1933), Société Nobel Française.
(30) Ger. Pat. 281,687 (July 14, 1913), F. Klatte and A. Rollett (to Chem. Fabrik Griesheim-Elektron).
(31) U.S. Pat. 1,241,738 (Oct. 2, 1918), F. Klatte and A. Rollett.
(32) U.S. Pat. 2,204,324 (June 11, 1940), L. C. Sohngen (to Las-Stik Mfg. Co.).
(33) U.S. Pat. 2,317,725 (April 27, 1943), K. Billig (vested in Alien Property Custodian).
(34) U.S. Pat. 2,413,239 (Dec. 24, 1946), G. J. Manson (to Shawinigan Chemicals Ltd.).
(35) U.S. Pat. 2,486,855 (Nov. 1, 1949), E. Lavin and C. L. Boyce (to Shawinigan Resins Corp.).

K. G. BLAIKIE AND T. P. G. SHAW

Polyvinyl Acetate Emulsions

Polyvinyl acetate emulsions (also referred to as dispersions or latexes) are the suspensions produced by the polymerization of vinyl acetate in water. They are used chiefly in the fields of adhesives (*q.v.*), paints (*q.v.*), textile finishes (see *Textile technology*), and coatings (*q.v.*).

Plauson (22) made the first polyvinyl acetate dispersion in Germany about 1929. Emulsions became available in the U.S. in 1938. Since then the use of the emulsion has grown rapidly until in 1952 about 25 million pounds of vinyl acetate was used for making emulsions in the U.S. alone, the price ranging from 18 to 24 cents per pound of emulsion. By far the greater portion of polyvinyl acetate resins is now sold in the form of emulsions.

The emulsions are milk-white liquids containing about 55% polyvinyl acetate, the balance being water, with small quantities of wetting agents and protective colloids. Their use eliminates the need for expensive, flammable, odorous, or toxic solvents, and for the recovery of such solvents. They are easy to apply, and the equipment is easy to clean with water, if done promptly. Emulsions also offer the advantage of high solids content with fluidity, since the viscosity of the emulsion is independent of the molecular weight of the resin.

Tables I and II give trade names and properties of many polyvinyl acetate dispersions and vinyl acetate copolymer dispersions.

In Europe, trade names for polyvinyl acetate emulsions are:

Calatac VA	Imperial Chemical Industries Ltd.
Emultex	Revertex Ltd.
Mowilith D-	Farbwerke Hoechst AG
Novylol	Société Nobel Française
Polimul	Dunlop Special Products
RHC *polyvinyl acetate emulsion*	R. H. Cole & Co., *Ltd.*
Emulsion Rhodopas	Société des usines chimiques Rhône-Poulenc
Texibond, Texicote, Texisize	Scott Bader & Co. Ltd.
Vinamul	Vinyl Products Ltd.
Vinavil	Rhodiatoce S.p.A.
Vinnapas Dispersion	Wacker-Chemie GMBH
Vipolit	Lonza Elektrizitätswerke und Chemische Fabriken

PROPERTIES

The specific gravity at 20°C. for all the emulsions is about 1.1. They generally possess a slight odor of residual monomer but if this is removed, by some such means as air blowing, the emulsions are virtually without odor. The traces of acetic acid which are present can be neutralized with a base such as ammonia, sodium bicarbonate, or triethanolamine, and in cases where the free monomer has been removed the pH of the resulting emulsion may be adjusted to remain constant at 7 or thereabouts. By the judicious selection of monomer concentration, protective colloid, emulsifying and wetting agents, method of polymerization and post-treatment, the properties can be varied to suit the end use. Such properties include average particle size and particle size range, polymer molecular weight, pH, emulsion viscosity, particle charge, adhesion, speed of tack, solvent tolerance, film characteristics and water resistance, and stability to storage, to freezing, to dilution, to mechanical action and to compounding (3,12,15, 17). Various resins, plasticizers, thickening agents, solvents, pigments, extenders, and

TABLE I. Commercial Polyvinyl Acetate Dispersions Manufactured in the U.S. and Canada in 1954.

Trade name	Manufacturer or supplier[a]	Polymer description	Total solids, %	Viscosity, poises[b]	Range of particle size, μ	Particle charge
Aerotex Resin 159	3	High molecular weight	55	3–6	1–2	–
Alk-O-Mer 8016	1	Suitable in washable paints	49–51	74 B[c]	0.1–0.3	0
Alk-O-Mer 8030	1	Hard, clear film, high gloss	54–56	35–50 B[c]	1–2	0
Bakelite Vinyl Acetate Latex WC-130	4	High-viscosity resin	55	15–25 B[d]	—	–
Beech-Nut Resin No. E-103	5	Tough, clear films	55	10–15 B[c]	1	–
Beech-Nut Resin No. EP-103	5	Preplasticized	55	10–15 B[c]	1	–
CRC Emulsion C	7	Adhesive grade	55	17–22 B[f]	0.8 av.	–
CRC Emulsion D	7	Free-filming, water-resistant	55	10–14 B[f]	0.6 av.	–
CRC Emulsion F	7	Paint grade	55	4–8 B[f]	0.9 av.	–
CRC Emulsion F20	7	Plasticized paint grade	55	—	0.9 av.	–
CRC Emulsion F60	7	Plasticized paint grade	55	—	0.9 av.	–
CRC Emulsion K	7	Medium-viscosity resin	35	2–4 B[f]	0.2 av.	–
Darex 86289	9	Borax-resistant	54–56	10–30 B[g]	1	–
Darex X52L	9	Medium molecular weight	54–56	3–6 B[g]	2–3	–
Darex X53L	9	Very high molecular weight	54–56	3–6 B[g]	1	–
Darex X56L	9	Similar to X53L, unstripped of residual monomer	54–56	3–6 B[g]	1	–
Darex X59L	9	Medium molecular weight	54–56	10–12 B[g]	0.5–5	–
Elvacet 80-900	10	Medium viscosity	55–57	8–10 B	1–3	–
Elvacet 81-900	10	Medium viscosity	55–57	8–10 B	1–3	–
Elvacet 81-1600	10	Medium viscosity	55–57	15–17 B	1–3	–
Filaseal Resin	2	Medium viscosity	55	—	—	–
Filaseal Resin H-20	2	Plasticized grade	55	—	—	–
Gelva Emulsion S-55	16	Low molecular weight, crosslinked	55 min.	11–13 B[c]	1–5	–
Gelva Emulsion TS-22	16	Medium viscosity	55 min.	3.5–6.5 B[e]	1–2	–
Gelva Emulsion TS-30	16	Medium viscosity	55 min.	12–14 B[e]	1–2	–
Gelva Emulsion TS-35	16	Medium viscosity	55 min.	8–11 B[e]	1–3	–
Gelva Emulsion TS-41	16	Medium viscosity	35 min.	2–4 B[e]	< 1	–
Gelva Emulsion TS-63	16	Low viscosity	55 min.	10–15 B[e]	1–2	–
Gelvatex	15a	Same as CRC emulsions				
Griffco-22	11	Medium viscosity	55 min.	9–12 B[g]	1–3	0
Griffco-33	11	Medium viscosity; water-resistant film	55 min.	15–20 B[g]	0.5–2	0
Griffco-44	11	Medium viscosity; borate- and phosphate-tolerant	55 min.	15–20 B[g]	0.5–2	0
Merlon KR-1	12	Tough film; softens at 91°C.	55 min.	9–11 B[e]	1	–
Merlon KR-2	12	Pliable; softens at 104°C.	55 min.	12–14 B[e]	1	–
Merlon KR-3	12	Brittle; softens at 104°C.	35 min.	2–4 B[e]	0.2	–

TABLE I. Commercial Polyvinyl Acetate Dispersions Manufactured in the U.S. and Canada in 1954 (*Continued*).

Trade name	Manufacturer or supplier[a]	Polymer description	Total solids, %	Viscosity, poises[b]	Range of particle size, μ	Particle charge
Merlon KR-4	12	Pliable; softens at 85°C.	55 min.	10–15 B[e]	2–3	–
Merlon KR-5	12	Brittle, hard resin	55 min.	5–8 B[e]	1.5–2	–
Merlon KR-6	12	Low molecular weight	55 min.	9–12 B[e]	1–10	–
Nopco 1572-B	14	Softens below 90°C.	55	9–12 B[g]	1–3	–
Nopco 1572-R	14	Heat seals at 220–230°F.	55	9–12 B[g]	1–4	–
Norvan X52L, etc.	18	Identical with Darex series	—	—	—	
Polyco 117-FR	6	Freeze-thaw stable emulsion similar to 117-SS	55	9.5–12 B[h]	2–10	0
Polyco 117-H	6	Medium particle size	55	10–15 B[h]	2–10	0
Polyco 117-SS	6	Stable to addition of water-soluble solvents	55	9.5–12 B[h]	2–10	0
Polyco 289	6	High-viscosity emulsion	56–57	33–37 B[h]	1–7	0
Polyco 505	6	Clear, water-resistant films	55	12–18 B[h]	1–5	0
Polyco 522	6	High-temperature color stability and water resistance	55	12–18 B[h]	1–5	0
Polyco 529	6	Deposits highly water-resistant films	55	15–20 B[h]	1–5	0
Polyco 570	6	Low-molecular-weight emulsion	35	20 B[h]	0.4–1.5	–
Polyco 577-G	6	Highly water-resistant	55	10–20 B[h]	0.4–1.5	0
Polyco 612	6	Higher-solids, fine-particle type	60	10–20 B[h]	0.5–2	–
Polyco 836-24	6	Ultra-fine-particle type; nonsettling textile finish	45	2.2–2.6 B[h]	< 0.5	–
Polyco 953-7A	6	Fine-particle type with low settling rate	55	12.5–16 B[h]	0.5–2	–
Polyco 1040-14B	6	Fine-particle size	55	10–13 B[h]	1–5	0
Resyn 10K01	13	Medium molecular weight	55	25 S[i]	< 1	0
Resyn 10K11	13	Standard adhesive base	55	20 S[i]	1–3	0
Resyn 10K21	13	Solvent-tolerant adhesive base	55	20 S[i]	1–3	0
Resyn 10K25	13	Clear, tough, water-resistant	55	25 S[i]	< 1	0
Vinac HF	8	Heat-seals at 110–120°C.	55	37–42 B[j]	1	0
Vinac P-100	8	Paint grade	57–58	6–9 B[j]	0.5–1	0
Vinac WR-20	8	Modified polyvinyl acetate	55	7–15 B	0.5–1	0
Vinac XX	8	Strong, clear, glossy films	55	8–15B	1	0
Vinrez 101	17	Medium viscosity	55 min.	10–12 B[k]	0.5–1	0

(*Continued*)

TABLE I. Commercial Polyvinyl Acetate Dispersions Manufactured in the U.S. and Canada in 1954 (*Concluded*).

Trade name	Manufacturer or supplier[a]	Polymer description	Total solids, %	Viscosity, poises[b]	Range of particle size, μ	Particle charge
Vinrez 202	17	Medium viscosity	55 min.	10–12 B[k]	1–4	0
Vinrez 202A	17	Medium viscosity	55 min.	12–15 B[k]	1–4	0
Vinrez 202H	17	High viscosity	55 min	18–23 B[k]	1–4	0
Wooncolloid	19	—	—	—	—	
Xyno Resin 362	15	Coarse-particle-size emulsion for textiles	55	—	—	0
Xyno Resin X99	15	Viscous dispersion of coarse particle size	50	—	—	+

[a] The numbers in this column refer to these companies:
1. Alkydol Laboratories, Inc., 3242 South 50th Ave., Cicero 50, Ill.
2. Amalgamated Chemical Corp., Rorer and Ontario Streets, Philadelphia 34, Pa.
3. American Cyanamid Co., Textile Resin Dept., Bound Brook, N.J.
4. Bakelite Co., Division of Union Carbide and Carbon Corp., 30 East 42nd St., New York 17, N.Y.
5. Beech-Nut Packing Co., Canajoharie, N.Y.
6. The Borden Co., Chemical Division, Polyco Dept., 101 Foster St., Peabody, Mass.; in Canada, Polyresins Ltd., 184 Laird Drive, Toronto 17, Ontario.
7. Canadian Resins and Chemicals Ltd., 600 Dorchester St. West, Montreal, Canada.
8. The Colton Chemical Co., Division of Air Reduction Co., Inc., 1545 East 18th St., Cleveland 14, Ohio.
9. Dewey and Almy Chemical Co., Division of W. R. Grace and Co., Cambridge 40, Mass.
10. E. I. du Pont de Nemours and Co., Electrochemicals Dept., Wilmington 98, Del.
11. Griffin Chemical Co., 1000 16th St., San Francisco 7, Calif.
12. Monsanto Chemical Co., Plastics Division, Springfield 2, Mass.
13. National Starch Products, Inc., Resin Division, 1700 West Front St., Plainfield, N.J.
14. Nopco Chemical Co., Harrison, N.J.
15. Onyx Oil and Chemical Co., Warren and Morris Streets, Jersey City 2, N.J.
15a. Shawinigan Chemicals Ltd., Shawinigan Bldg., Montreal, P.Q., Canada.
16. Shawinigan Resins Corp., Springfield, Mass.
17. Stein, Hall and Co., Inc., 285 Madison Avenue, New York.
18. R. T. Vanderbilt Co., Inc., 230 Park Ave., New York 17, N.Y.
19. Woonsocket Color and Chemical Co., Woonsocket, R.I.

[b] B = Brookfield viscometer; S = Stormer viscometer.
[c] 77°F.
[d] 20°C., No. 4 spindle, 60 r.p.m.
[e] 25°C., No. 3 spindle, 30 r.p.m.
[f] 20°C., No. 3 spindle, 20 r.p.m.
[g] 25°C., No. 3 spindle, 60 r.p.m.
[h] 25°C., LVF, No. 2 spindle, 12 r.p.m.
[i] 72°F., standard paddle, 100 r.p.m., calibrated on standard liquids.
[j] 20°C.
[k] 24°C.

some dyes may be added, but caution is necessary and it is advisable to adhere closely to the manufacturer's directions. Plasticizers are often added to provide increased flexibility to the dried film, but it is unusual to incorporate these before making the final formulation since their presence may adversely affect stability, particularly in cold weather.

When the emulsion is applied to a surface, water is lost by evaporation, and by absorption if the surface is porous. The particles stick together and eventually coalesce to form a tough, more or less clear, continuous coating. The clarity is often improved by the presence of plasticizer which also enhances the film's resistance to water. Films from most emulsions containing polyvinyl alcohol as the protective colloid are liable to reemulsify on contact with water unless they contain relatively large quantities of plasticizer or solvent. However, the best adhesives stem from these polyvinyl alcohol-containing emulsions, so that a compromise between bond strength and

TABLE II. Vinyl Acetate Copolymer Dispersions Manufactured in the U.S. in 1954.

Trade name	Manufacturer or supplier[a]	Polymer description	Total solids, %	Viscosity, poises[a]	Range of particle size, μ	Particle charge
Beech-Nut Resin No. EC-103	5	Clear flexible film with high gloss, excellent water resistance	55	10–15 B[e]	1	–
Darex Everflex A	9	Clear, tough, permanently flexible films	54–56	10–12 B[e]	< 2	–
Darex Everflex B	9	Softer, but otherwise similar to A	54–56	10–12 B[e]	< 2	–
Darex Everflex G	9	Special scrub-resistant grade for water-base paints	50–52	3–5 B[e]	< 2	–
Griffco-55	11	Medium viscosity, clear; medium flexible	55 min.	15–20 B[e]	0.5–2	0
Norvan G, etc.	18	Identical with Darex Everflex G, etc.	—	—	—	
Polyco 337-XS	6	Specially modified emulsion for textile finishes	40	< 4 B[h]	0.4–1.5	–
Polyco 470	6	A self-curing Portland cement additive	50	12–18 B[h]	2–4	0
Polyco 507	6	Precatalyzed crosslinking adhesive base	50–53	11–15 B[h]	2–10	0
Polyco 520	6	Highly crosslinking adhesive base used with separate catalyst	52–54	11–15 B[h]	2–10	0
Polyco 547	6	Low crosslinking adhesive base used with separate catalyst	53–55	11–15 B[h]	2–10	0
Polyco 564	6	Medium crosslinking adhesive base used with separate catalyst	55–57	17–25 B[h]	2–10	0
Resyn 12K51	13	Internally plasticized, clear, tough, flexible	55	23 S[i]	< 1	0
Resyn 14K11	13	More polar, enhanced adhesion	51	30 S[i]	1–4	0
Resyn 22K11	13	Strong, water-resistant binder	55	6 S[i]	< 1	0

[a] See Table I for footnotes.

water resistance has often to be made. Emulsions containing gum arabic, hydroxyethyl cellulose, or carboxymethyl cellulose will film without addition of plasticizer or solvent. These films do not reemulsify under water but do whiten somewhat, clearing again as they dry out. This whitening, which is due largely to the presence of the water-sensitive colloids and wetting agents, decreases on successive cycles of wetting and drying, as the water-sensitive ingredients are leached.

Polyvinyl acetate emulsion films have good adhesion to most surfaces, and good binding capacity for pigments and fillers. Plasticized films have good strength and flexibility at ordinary temperatures. The films are unaffected by light, oxygen, chlorine in moderation, and dilute solutions of acid, alkali, and salts. The films are also inert to oils, fats, waxes, and greases, unless these are largely aromatic in character.

Solvents such as acetone, alcohol, ethyl acetate, benzene, and toluene will dissolve or, at any rate, swell the film. An important property of a polyvinyl acetate film is its permeability to water vapor. This allows the film to be laid down on a damp surface, the trapped moisture gradually passing through the film without lifting or blistering.

MANUFACTURE

Polyvinyl acetate emulsions can be prepared by batch, by delayed monomer addition, or by continuous processes.

Batch Process. Monomeric vinyl acetate is added to an aqueous solution of the protective colloid with good stirring. The resulting mixture, which comprises small droplets of monomer suspended in the aqueous medium, is heated under reflux with a catalyst until polymerization is virtually complete (23). The reaction is exothermic but may be easily controlled. The particle size under these conditions is relatively large (3–6 μ) but can be reduced to some extent by using 0.1–0.5% of a surface-active agent, usually anionic or nonionic. Water-soluble catalysts such as hydrogen peroxide or peroxysulfate are suitable. With catalysts which are soluble in the oil phase (benzoyl or lauroyl peroxide), bulk polymerization of the monomer droplets takes place and quite coarse particles of the order of 100 μ result, unless the stirring is very vigorous. The addition of thiourea or its derivatives will result in finer particles by inhibiting the bulk polymerization of the droplets.

Delayed Addition Process. The delayed process is essentially a batch process, but only about 10% of the monomer and all the stabilizers and water are added at first to the kettle with 25–30% of the catalyst. The charge is stirred strongly and heated to 75–80°C., maintaining a slow reflux of monomer. The balance of the monomer and the remaining catalyst are added slowly to maintain a reaction temperature of 78–80°C. After all the monomer is in, an extra amount of catalyst is added to finish the reaction, and the temperature is slowly raised to 90°C. as the reflux disappears (24). The residual monomer may then be removed by blowing with air or by distillation.

Delayed addition emulsions are particularly suitable for outdoor paints and other coatings because of the small particle size (0.2–1.5 μ), free-filming properties, gloss, and low water sensitivity. The delayed addition processes employed at Hoechst and Burghausen in Germany have been described in detail (2,7,14).

Continuous Process. This method has largely supplanted the batch process. Two or more kettles fitted with efficient stirrers are used (26). Catalyst, monomer, and the stabilizer solution are run separately into the first kettle held at 70–80°C., and the overflow runs to the second kettle heated to 80–90°C., where additional catalyst is metered in. The effluent from the first kettle contains particles of moderate size (1–3 μ) while the residual monomer under the influence of the additional catalyst in the second kettle forms particles ranging from 0.2 to 1 μ. The wide range of particle size in the finished emulsion (0.2–3.5 μ) makes it well suited for adhesive applications; the larger particles prevent excessive penetration into porous surfaces, while the smaller particles provide good packing.

Shipping and Handling. Polyvinyl acetate emulsions should not be handled in mild steel or copper. Piping and tanks may be aluminum, stainless steel, plastic, rubber, wood, glass, or enameled ware. Some of the special bronzes such as aluminum bronze may be used in centrifugal or gear-type pumps, which are preferred for use with emulsions. Dissimilar metals in contact should be avoided, as they may cause coagu-

lation. The emulsions are shipped in resin-lined steel drums, stainless steel tank cars or tank trucks. They should be protected from freezing and high temperatures (above 100°F.), and containers should be kept tightly closed to prevent the evaporation of water, which would result in the formation of sludge or skins (3,12,18).

USES

Adhesives. Polyvinyl acetate emulsions have excellent adhesion to a wide variety of materials, and adhesives based on these emulsions usually produce strong flexible bonds. Adhesives are of the wet-bond, heat-sealing, or pressure-sensitive types. The preparation of adhesives provided the largest outlet for polyvinyl acetate emulsions in 1954.

In certain applications such as wood adhesives, unmodified emulsions may be unsatisfactory because of their tendency toward cold flow, their low resistance to heat (softening at 110–160°F.), and also their low resistance to water or moisture, and to solvents such as alcohol.

Cold flow (slip or creep under static load or continuous stress) is reduced by the addition of 0.1–15% on resin solids of a methyl vinyl ether–maleic anhydride copolymer (33) or of urea-formaldehyde resins. The adhesive with urea-formaldehyde sets quickly at room temperatures (28). A phenol-formaldehyde resin raises the softening point and solvent resistance (20). Inert fillers, such as wood flour, walnut-shell flour, and clay, raise the softening point slightly. Adhesion and heat stability are improved by the addition of up to 3% of high-viscosity polyvinyl alcohol, which also reduces the weakening effect of fillers and increases the working range by reducing the rate of evaporation of water. The period of dampness of the film may be extended by addition of ethylene glycol. The water resistance and heat-sealing temperature are raised by adding, just before use, dimethylolurea or trimethylolmelamine. Water resistance is also increased by the addition of various substances such as rosin extract (21), diacetin (32), hexylene glycol (27), 1,1-di-*n*-butyl- or 1,1-diethylurea (29), triethylene glycol, dipropylene glycol, diethylene glycol monobutyl (or diethyl) ether, succinic acid, butyramide, ethylene glycol monoethyl ether acetate, and benzamide (30). Polyvinyl acetate emulsions may be thickened with methyl cellulose, sodium carboxymethyl cellulose, or polyvinyl alcohol-acetate without affecting the transparency. Starch or dextrin may be used to improve the initial tack and thicken the adhesive, although the water resistance is lowered.

For smooth nonabsorbent surfaces such as metals, porcelain, mica, or stone, the adhesive should be applied to both surfaces and allowed to dry to a definite tack; the bond is then made by applying a slight pressure.

The soft pressure-sensitive type of adhesive with lower bond strength is obtained by adding 20% or more of a plasticizer such as dibutyl phthalate, and is used, for example, in cohesive gauze bandages.

Among the advantages of wet-bond adhesives based on polyvinyl acetate emulsions, for porous materials such as paper, fiber, cloth, leather, cork, or wood, are their fast tack or rapid rate of setup, requiring short pressing and assembly times. They require no organic solvents, and are colorless, mold-resistant, and free from undesirable odor. They offer uniformity of viscosity. They have good stability in storage and long working life, with no wastage of unused adhesive. They do not depend on heat or catalyst for curing. One of the most important uses of these adhesives is in the lamination or bonding of materials such as paper, cellulose acetate film, cellophane,

textiles, and aluminum foil to paper. Viscose warp is joined to paper or plastic film as a nonwoven fabric (see Vol. **13,** p. 865). Colorless, odorless, tasteless, and nontoxic adhesives are provided for waterproof food packages, milk cartons, paper cups, and drinking straws. Book-binding adhesives are another application, while the edges of stacked paper may be glued by "padding cements."

During the rubber shortage of World War II, polyvinyl acetate emulsions were used as an extender or replacement for rubber latex adhesives in the manufacture of shoes. Most of this market later returned to rubber adhesives because of their dry tack and greater resilience, but the resin emulsions are still preferred in some leather adhesive applications.

The good binding power of polyvinyl acetate emulsions makes them suitable for the manufacture of reconstituted leather, which is made by binding together leather scrap with these emulsions and rolling into a tough sheet. This material is suitable for gaskets, floor coverings, insulation, and sole or heel stock. In a similar manner ground cork, sawdust, waste paper, asbestos, or vermiculite may be bound and compressed into useful articles such as floor coverings, toys, and mannequins (1). Emulsions have also proved satisfactory foundry core binders (6).

Paints. Paints based on water emulsions of polyvinyl acetate solutions were being developed in Canada in 1935, and the true polyvinyl acetate dispersions in England, Canada, and Germany about 1939. During and subsequent to the war years their use for both interior and exterior application was expanded until in 1953 about 15 million pounds of vinyl acetate monomer was consumed in Europe in this field. In the U.S. and Canada, polyvinyl acetate latex paints reached commercial development for interior use about 1946 (18).

It was not until 1950 that commercial production of exterior paints based on polyvinyl acetate emulsions was started. In 1952, 10 million pounds of emulsion was used in this application, and paints prepared from them are now well established as primers or sealers and as surface coatings over masonry, stucco, and concrete.

Polyvinyl acetate emulsion paints form flexible, durable films with good adhesion to clean surfaces including wood, plaster, concrete, stone, brick, cinder blocks, asbestos board, asphalt, and tar, paper and wall boards, aluminum, and galvanized iron; adherence is also good on surfaces already painted if the surfaces are free from dirt, grease, and rust. Emulsion paints are easy to apply by spray gun, roller-coater, or brush. The paint may be thinned with water, and brushes or coaters cleaned with soap and tepid water. There is no unpleasant odor, and no risk of fire or explosion. The paint is usually dry to the touch in 20 minutes to 2 hours, and two coats may be applied the same day.

Polyvinyl acetate paint films are stable in sunlight and ordinary temperatures, and do not oxidize or discolor. The films are resistant to oils, fats, greases, gasoline, and kerosene and are easy to clean by washing with soap and water. Stubborn grease marks can often be removed with kerosene or carbon tetrachloride. Ink stains can be bleached with Javelle water (a hypochlorite solution) without danger to the coating, provided organic dyes susceptible to hypochlorite have not been incorporated into the formulation. Polyvinyl acetate emulsion films are permeable to water vapor and resistant to alkali, and paints may therefore be applied over relatively new plaster, stucco, or concrete without later blistering or peeling. The films may be formed over damp surfaces and, since they do not transmit liquid water, may be used to waterproof porous building surfaces.

Emulsions for paints are usually plasticized. A plasticizer such as dibutyl phthalate improves the gloss, tensile strength, and elongation of the paint film. Blends of esters, or Flexol 3GH or 4GO (Carbide and Carbon Chemicals Corp.), improve the low temperature flexibility and minimize loss of plasticizer due to evaporation and migration. The latter fault does not appear to be as serious in practice as laboratory tests on migration would indicate. No failures attributable to this cause have been observed in paints applied to exterior walls on the West Coast after four years exposure.

In preparing a paint, the plasticized polyvinyl acetate emulsion is usually added with constant stirring to an aqueous dispersion of the pigments. A thickener or stabilizer may be incorporated into the plasticized emulsion, the pigment dispersion or their mixtures.

Suitable white pigments are titanium dioxide and lithopone. Most standard colored pigments can be adapted to the polyvinyl acetate system, and several pigment manufacturers now have colored bases especially prepared for tinting purposes. Fillers or extenders include talc, mica, china clay, blanc fixe, whiting, and diatomite. The pigment may be dispersed in water by milling in a colloid or ball mill in the presence of a dispersing or wetting agent and a thickening agent. An antifoam agent such as tri-*n*-butyl phosphate (0.06%) may be used to break any foam produced during milling. Methyl cellulose is a common thickening agent, while others mentioned in the literature include sodium carboxymethyl cellulose, ammonium polymethacrylate, sodium silicate, and soy protein.

TABLE III. Typical Paint Formulations to Make 100 U.S. Gallons.

Component	No. 1	No. 2
Pigments, TiO_2, etc.	250 lb.	126 lb.
Lithopone	—	161
Fillers, barytes, mica	60	—
Wetting agent	1.7	8.9
Protective colloid	6.0	5.4
Antifoam agent (tri-*n*-butyl phosphate)	0.7	—
Water	419	350
Solvent	—	33
Polyvinyl acetate emulsion	335	378
Dibutyl phthalate	28	31
Total	1,100 lb.	1,093 lb.

An alkyd resin with lead and cobalt naphthenates as driers is sometimes added to improve adhesion, stain removal, washability, or freeze-thaw stability (25,31). Various glycols (0.5–4% by weight of total paint) will improve the brushing and leveling characteristics by increasing the drying time. Ammonium oleate, sodium benzoate (0.35%), or dicyclohexylamine nitrite (VPI) (0.02%) may be used as a rust inhibitor.

Water-base paints should not be used directly over calcimine or water-soluble glue sizes, as these will partially dissolve and adversely affect the leveling properties of the paint. Iron and steel should be primed with a rust-inhibiting coat, and it is

usually desirable to prime new unpainted wood as water may cause the grain to swell. Dry porous surfaces should be dampened with water or primed with polyvinyl acetate sealer or diluted emulsion to avoid undue absorption which results in a chalky film.

Polyvinyl acetate emulsion primer-sealers have good adhesion and "hold out;" that is, they will bridge pores and fine cracks to present an even surface for subsequent painting with oil, latex, or emulsion finishes. Since hiding power is of secondary importance, the primer-sealer may have a lower pigment loading than paint, and most of the pigment can be of the filler type. There may be about 18% solid resin and 10–20% pigments in an average formulation. Some prefer as high as 30% extender pigments, and they tint the primer-sealer.

Textile Finishing. Polyvinyl acetate emulsions find wide application as textile finishes because of their low cost and good adhesion to natural and synthetic fibers (see *Textile technology*, Vol. **13,** p. 884).

In textile piece goods finishing, the dispersions diluted with water to 1–3% resin are most often used to obtain a stiff or crisp hand on woven cotton fabrics (5,11,12,16, 19). Concentrations of 2–20% emulsion are recommended for bodying, stiffening, and bonding. Major applications include the stiffening of felts and the binding of nonwoven fabrics. Finishes to improve the snag resistance and body or hand of rayon or nylon hosiery are based on polyvinyl acetate emulsions (5,10,16). A permanent starch for household use is usually based on an emulsion of polyvinyl acetate or its copolymer with acrylic ester, diluted to about 10% solids.

Polyvinyl acetate emulsions are used to prime-coat fabrics to improve adhesion of subsequent coatings, or to make them adhere better to plastic film. Plasticized emulsions are applied, generally by roller-coating, to the backs of finished rugs and carpets to bind the tufts in place and to impart stiffness and handle. For upholstery fabrics woven from colored yarns, polyvinyl acetate emulsions may be used to bind the tufts of pile fabrics or to prevent slippage of synthetic yarns.

Paper. Polyvinyl acetate emulsions added to paper by size press or calender application impart improved stiffness, grease resistance, good color, and aging properties (13). Polyvinyl acetate emulsions are used in Europe as a wallpaper coating to yield a high-quality, greaseproof, washable finish. In paper finishing the polyvinyl acetate emulsions make excellent binders for the clay coatings used to give the desired ink retention and printing qualities. Emulsion added to the pulp improves the dry strength of the paper. This has been carried on commercially in a few European countries. Flexible paper board with good shock resistance is prepared from emulsion with up to 4% dibutyl phthalate.

Coatings. Polyvinyl acetate emulsions are used as surface coatings in the manufacture of such articles as floor coverings and seat covers. During periods of scarcity of linseed oil in Europe, emulsions have been used in the preparation of oilcloth substitutes and artificial linoleum. Floor finishes (waxes or polishes) based on fine-particle polyvinyl acetate emulsions have high gloss and good durability.

Polyvinyl Acetate Emulsions in Cement. Emulsion-cement mixes were developed in England during World War II as nonslip, resilient floorings on battleship decks. The mixtures have excellent adhesion to iron, steel, concrete, and bricks, and may be compounded to avoid shrinking or expanding on setting. Flooring compositions are smooth and tough, and resistant to grease, oils, dirt, and wear. In England emulsion-cement flooring has often been used in housing projects where jointless flooring was specified, as well as in factories, restaurants, and assembly halls (4,9).

EMULSION COPOLYMERS WITH VINYL ACETATE

Copolymer emulsions of vinyl acetate with such materials as vinyl benzoate, vinyl crotonate, vinyl stearate, alkyl acrylates and alkyl maleates and their acids, have been prepared, and some are available commercially. Such materials tend to yield more flexible films than vinyl acetate and accordingly require less plasticization. It has been reported that they have a high blocking temperature and in some applications show a high order of water resistance (8). They are recommended for the same group of applications as polyvinyl acetate emulsions.

Bibliography for Polyvinyl Acetate Emulsions

(1) Baum, S. J., *F.I.A.T. Final Rept.* **1108**; cf. Bidlack, V. C., Curtis, F. J., and Harris, J. M., P.B. 208, p. 30 (Publication Board).
(2) Baum, S. J., and Dunlop, R. D., *F.I.A.T. Final Rept.* **1102**; cf. Blaylock, P. W., and Andersen, A. H., *B.I.O.S. Final Rept.* **1161**; Raine, H. C., *B.I.O.S. Final Rept.* 744; Kline, G. M., Rooney, J. H., Crawford, J. W., and Cove, T., P.B. **949** (*C.I.O.S.* 29-62), pp. 55-6, 81-2.
(3) Borden Company, *Technical Bull.* P-16, *Polyvinyl Acetate Emulsions*, Peabody, Mass.
(4) Borden Company, *Technical Data Sheet* P-35, 1954.
(5) Borden Company, *Technical Bull.* P-56, *Polymers for Textiles*, 1954, Peabody, Mass.
(6) Cola, G., *Materie plastiche*, **14**, 1-7 (1948).
(7) DeBell, J. M., Goggin, W. C., and Gloor, W. E., *German Plastics Practice*, DeBell and Richardson, Springfield, Mass., 1946, pp. 103-111.
(8) Dewey and Almy Chemical Co., *Bull.* E-9, Cambridge, Mass., 1954.
(9) Geist, J. M., Amagna, S. V., and Mellor, B. B., *Ind. Eng. Chem.*, **45**, 759-67 (1953); cf. Farmer, N. W., *Plastics* (*London*), **15**, 89 (1950).
(10) Mauersberger, H. R. (ed.), *American Handbook of Synthetic Textiles*, Textile Book Publishers, a Division of Interscience, N.Y.-London, 1952, Ch. 17.
(11) *Modern Plastics*, **31**, No. 1, 103-105, 185-6, 188, 190-3, 198, 200 (1953).
(12) Monsanto Chemical Co., "Merlon KR Series," *Technical Bull.* PTI 50-15.1, Springfield, Mass.
(13) Reiter, R. W., *Tappi*, **36**, No. 6, 60A, 62A, 64A (1953).
(14) Richardson, R. E., Kern, J. G., Murray, R. L., and Sudhoff, R. W., P.B. 218, pp. 53-4, 58-61.
(15) Schildknecht, C. E., *Vinyl and Related Polymers*, Wiley, N. Y., 1952, pp. 333-41.
(16) Shapiro, L., *Am. Dyestuff Reptr.*, **43**, 132-40, 691-6 (1954).
(17) Shawinigan Products Corp., *Gelva*, N.Y., 1952.
(18) Shawinigan Products Corp., *Gelva Emulsion for Paint*, N.Y., 1954.
(19) Trevor, J., *Textile Recorder*, **68**, No. 809, 77 (1950).
(20) Brit. Pat. 574,459 (Jan. 7, 1946), High Duty Alloys Ltd. and L. Whitby.
(21) U.S. Pat. re-issue 23,164 (Nov. 1, 1949) of U.S. 2,435,909 (Feb. 10, 1948), N. G. Tompkins (to Dewey and Almy Chemical Co.).
(22) U.S. Pat. 2,127,135 (Aug. 16, 1938), H. Plauson (to Röhm and Haas Co.).
(23) U.S. Pat. 2,444,396 (June 29, 1948), H. M. Collins and G. O. Morrison (to Shawinigan Chemicals Ltd.).
(24) U.S. Pat. 2,508,341-3 (May 16, 1950), W. K. Wilson (to Shawinigan Resins Corp.).
(25) U.S. Pat. 2,567,678 (Sept. 11, 1951), G. O. Morrison (to Shawinigan Products Corp.).
(26) U.S. Pat. 2,587,562 (Feb. 26, 1952), W. K. Wilson (to Shawinigan Resins Corp.).
(27) U.S. Pat. 2,588,543 (Mar. 11, 1952), W. G. Kunze and R. B. Evans (to Le Page's Inc.).
(28) U.S. Pat. 2,592,510 (April 8, 1952), G. S. Casebolt (to American Cyanamid Co.).
(29) U.S. Pat. 2,595,796 (May 6, 1952), W. G. Kunze and R. B. Evans (to Le Page's Inc.).
(30) U.S. Pat. 2,595,952-7 (May 6, 1952), W. G. Kunze and R. B. Evans (to Le Page's Inc.).
(31) U.S. Pat. 2,601,315 (June 24, 1952), G. O. Morrison and D. Schoenholz (to Shawinigan Products Corp.).
(32) U.S. Pat. 2,628,948 (Feb. 17, 1953), W. G. Kunze and R. B. Evans (to E. I. du Pont de Nemours and Co.).
(33) U.S. Pat. 2,677,672 (May 4, 1954), S. B. Luce (to Swift and Co.).

K. G. BLAIKIE AND M. S. W. SMALL

POLYVINYL ALCOHOL

The term polyvinyl alcohol includes all resins made by the hydrolysis of polyvinyl acetate. The properties vary according to the molecular weight of the parent polyvinyl acetate and the extent of hydrolysis. The structure of polyvinyl alcohol obtained by complete hydrolysis may be represented by $—CH_2CHOH(CH_2CHOH)_n—$, where n is related to the molecular weight of the parent resin. On partial hydrolysis, proportional amounts of residual $CH_3COO—$groups are distributed along the chain in place of OH, and the amount of such acetate groups expressed as a percentage is the *acetate content*; thus in a polyvinyl alcohol of 70% acetate content, 30% of the acetate groups of the original polyvinyl acetate were hydrolyzed to hydroxyl groups, and 70% remain as acetate groups. In commercial polyvinyl alcohol, the expression "low acetate," covers the range up to 15%, "medium acetate" 15–45%, and "high acetate" over 45%. Grades of polyvinyl alcohol are expressed, by Shawinigan Chemicals Ltd., by two numerals as 67/6 or 45/15. The number before the slant is the acetate content; the second number is the grade (proportional to the molecular weight) of the original polyvinyl acetate.

The chief uses of polyvinyl alcohol are as emulsifiers, adhesives, solvent resistant film, or moldings and extrusions. Recent developments are modified polyvinyl alcohol fibers that have been developed in Japan and polarizing films by the Polaroid Corp. for viewing 3D moving pictures.

The materials are shipped as white powders or granules. A large series of grades differing in acetate content and molecular weight is available.

Properties

Polyvinyl alcohol, white powder or granules, is stable in color up to 140°C. On prolonged heating at 160–170°C., it darkens in color and becomes insoluble in water. At over 170°C., ether formation occurs; over 200°C. it softens, and at still higher temperatures decomposes with carbonization. Under high pressures at 200–250°C. a moldable resin of slightly modified solubility is obtained (3,6,9,15,17,21). Its heat of combustion is 5902 cal./g. (3,15,17,21). The burning rate of polyvinyl alcohol film is slow. The densities and refractive indexes of resins of various acetate contents are given in Table I (10). The coefficient of linear expansion of polyvinyl alcohol is 7 to 12×10^{-5} (2).

Polyvinyl alcohol forms a reversible colloid in hot water, which is insoluble in cold water and may be purified by dialysis. In water at 20°C., polyvinyl alcohol up to

TABLE I. Density and Refractive Index of Polyvinyl Alcohol.

% acetate in resin	d_{20}^{20}	n_D^{20}
0	1.329	1.557
5	1.322	1.553
10	1.316	1.548
20	1.301	1.539
30	1.288	1.530
40	1.274	1.521
50	1.260	1.512
60	1.246	1.503
70	1.232	1.494

about 10% acetate content will swell; from 10–38% acetate content it is soluble; at 38–75% acetate it will form a thin mobile gel; and at higher acetate contents it is insoluble. In water at 100°C., polyvinyl alcohol at 0–38% acetate content is soluble; at 38–75% acetate content it forms a gelled slurry; at higher acetate contents it is insoluble; the addition of 40% ethyl alcohol will extend the range of solubility to resins of about 75% acetate content. In a 35:65 acetone-water mixture at 25°C. polyvinyl alcohols of up to 70% acetate content are soluble, and when the proportions are reversed at this temperature, resins of 35–99% acetate are soluble.

Polyvinyl alcohol above a 45% acetate content is soluble in cresylic acid, and above an 80% acetate content in liquid sulfur dioxide. Polyvinyl alcohols of low acetate content, and depending somewhat on the degree of polymerization, are soluble in hot solvents, such as acetic acid, formamide, glycerol, glycol, thiodiglycol(2,2′-thiodiethanol), acetamide, urea, amino hydroxy compounds, and phenol; on cooling, these solutions gel. However, if the phenol contains a trace of water, the solution remains liquid on cooling (6).

Polyvinyl alcohols of low acetate content are insoluble in and almost unaffected at ordinary temperatures by gasoline (either leaded or containing 24% alcohol and 10% benzene), kerosene, benzene, xylene, methylene dichloride, trichlorethylene, carbon tetrachloride, monochlorbenzene, methanol (anhydrous), ethyl alcohol (anhydrous), ethylene glycol, acetone, furfural, methyl acetate, ethyl acetoacetate, di-Oxane, formamide, diacetone alcohol, fenchyl alcohol, cyclohexanol, butanol, butyl carbitol, diethylene glycol, cresylic acid, monoethanolamine, triethanolamine, morpholine, quinoline, pyridine, nitrobenzene, ether, and aniline (8,10).

Examples of plasticizers that are compatible with polyvinyl alcohols are (10): for resins of 2.5% acetate content glycerol is by far the best, and diethylene glycol and ethylene glycol are also used; for resins of 45% acetate content glycerol, diacetin, triacetin, dimethyl phthalate, urea, and mono- or diethanolamine are used.

The osmotic pressure (14) of a polyvinyl alcohol solution of 1.2 g./100 ml. water (low acetate content, low molecular weight) is 0.008 atm. The viscosities in poises of polyvinyl alcohol of various acetate contents in 4, 8, and 12% solutions in water at

TABLE II. Viscosity of Polyvinyl Alcohol Solutions at 20°C.

Molecular weight, parent PV acetate	% acetate content	Viscosity, poises		
		4% soln.	8% soln.	12% soln.
10,000	20	0.0165	0.026	0.045
15,000	20	0.024	0.054	0.125
33,000	5	0.048	0.18	0.65
33,000	20	0.045	0.16	0.52
135,000	5	0.26	5.5	28
135,000	30	0.30	—	—
400,000	1	0.50	16	40
400,000	40	0.70	—	—

20°C. are given in Table II (10). The hydroscopicity (2) of several grades of high molecular weight–low acetate material is shown below:

Relative humidity, %	35	55	80	100
Per cent gain in weight	1–2.5	3–8	7–16	25–50

The abrasion resistance of polyvinyl alcohol is 10 times that of rubber (6,8), and its hardness (2), as measured by the Shore durometer, is 10–100 (plasticized). The tensile strength and elongation (at break) of low-acetate material is given in Table III (6). The cold flow (8) (per cent deformation of a 0.5 in. cube subjected to 4000 p.s.i. for 24 hr. at 120°F., and then allowed 24 hr. to recover) of polyvinyl alcohol is

TABLE III. Tensile Strength and Elongation (at Break).

	Extruded		Pressed	
Temp., °C.	Tensile strength, p.s.i.	Elongation, %	Tensile strength, p.s.i.	Elongation, %
−32	7650	30	7400	40
−18	6770	85	6760	85
0	6760	99	3640	267
25	5200	225	2110	445
46	3530	255	1610	520
66	3090	300	1490	590
80	2110	340	1250	620

63.4%. The softening points of several grades of polyvinyl alcohol are given below (10):

Grade	67/6	46/6	46/15
Softening point, °C.	132.4	148	162

The heat sealing temperatures (10,22) of resins of various acetate contents under pressures of 10 p.s.i. for 30 seconds are:

Per cent acetate	25	35	45	55	65	75
Heat sealing temp., °C.	195	180	163	148	133	118

The thermal conductivity (8) of polyvinyl alcohol in cal./(sec.)(sq.cm.)(°C./cm.) is 5×10^{-4} for the extruded resin and 18×10^{-4} for the molded resin.

The dielectric constants (4,6) and power factors at various temperatures are given in Table IV. The electrical resistivity (8) in (ohm)(sq.cm.)/(cm.) is $3.1 \times 3.8 \times 10^{7}$.

TABLE IV. Dielectric Constant and Power Factor.

Temp., °C.	Dielectric constant	Power factor, ($10^6 \sim$)
25	5.9	0.12
50	7.5	0.16
75	10.8	0.18
87.5	13.6	0.176

The permeability of polyvinyl alcohol films (8) in liters/sq.m. over a 24 hr. period for each 0.01 cm. thickness is: hydrogen, 1.41; oxygen, 0.51; and acetylene, 2.34.

The infrared absorption spectrum was determined by Blout and Karplus (1). The light transmitted by polyvinyl alcohol film at various wave lengths is given below (2):

Wave length, A.	2536	3130	3650
Per cent transmission	77.5	72.9	81.1

Toxicity. Metabolism tests on mice show no poisonous effects (3,9). Although some workers report no harmful effects are shown by intravenous, intramuscular, or subcutaneous injections (5,6), it is unsuitable for use as a blood substitute (2) as it can cause a decrease in the amount of red corpuscles and increase the sedimentation rate to eventual coagulation (5,6) when used in large amounts. Humans show no harmful effects when polyvinyl alcohol is used in surgery or as a carrier for medicaments (6). It is not broken down in the body and will remain as a foreign substance (2), hence care should be exercised not to inhale the dust into the lungs.

REACTIONS

Monomeric vinyl alcohol, $CH_2{=}CHOH$, is the enol of acetaldehyde (*q.v.*) and is unknown in the free state, although some of its derivatives such as mercury compounds are fairly stable. Polyvinyl alcohol was first mentioned by Herrmann and Haehnel (3,6,15,17,21) in 1927; they made it by saponification of polyvinyl esters.

Polyvinyl alcohol shows all typical alcohol reactions such as reaction with acids or anhydrides to form esters and with aldehydes or ketones to form acetals (see "Polyvinyl acetals"). Polyvinyl alcohol bears a similarity to the carbohydrates in that it does give the Carletti (thymol and menthol) and Fleig and Ihl (indene and oil of peppermint) carbohydrate reactions (3). It does not give a lignin reaction. Like starch it gives a violet color with iodine. It is stable to degradation (6,13).

Acetylene, the Freons, butane, propane, or sulfur dioxide do not affect polyvinyl alcohol at room temperature (8).

An insoluble yellow product containing 10% chlorine is obtained by the addition of chlorine at 20°C. The chlorine is believed to have replaced some hydroxyl groups and is removed with difficulty by boiling with caustic, leaving an insoluble modification of polyvinyl alcohol. At 40°C., the chlorination product is black and contains about 13% chlorine which is readily removed by dilute cold caustic, giving a lighter colored product. In this case the chlorine is believed to be only loosely attached. Bromine also reacts in a similar manner. Iodine gives a violet color even in low concentrations, but in the latter case the color may only appear after days. Iodine and polyvinyl alcohol in presence of potassium carbonate give iodoform (3,6).

Polyvinyl alcohol is not attacked by compressed oxygen at temperatures down to −70°C. (8). With 30% hydrogen peroxide, acetic acid and carbon dioxide but no succinic acid are formed (6,12). Potassium permanganate oxidizes polyvinyl alcohol only very slightly if at all (6). Chromic acid yields a brown insoluble mass which contains some of both the starting materials (6). This is made use of in printing techniques. Concentrated nitric acid forms polyvinyl nitrate in the cold (10) but oxidizes it on heating with the evolution of nitric oxide and formation of oxalic acid (7). There is no oxidization with periodic acid (6).

Because of its resistance to oxidation, polyvinyl alcohol of low and medium acetate contents is practically immune to deterioration by ageing (9).

Dilute or concentrated alkalies or acids attack polyvinyl alcohol. With stoichiometric amounts of sodium hydroxide the sodium polyvinyl alcohol trihydrate is said to be formed (3). On oxidizing fusion with solid caustic, oxalic and higher dicarboxylic acids may be formed (18). Esters of polyvinyl alcohol may be made using acid anhydrides or chlorides.

Extremely good adhesives are produced by reaction of aqueous polyvinyl alcohol

with aldehydesulfonic acids (19), such as acetaldehydedisulfonic acid (formylmethanedisulfonic acid) and benzaldehydesulfonic acid (formylbenzenesulfonic acid).

Manufacture

Polyvinyl alcohol is produced by either acid or alkaline hydrolysis of polyvinyl esters, usually the acetate. The resins made by the two processes differ somewhat, and the acid process product may contain some ether groups.

Acid Process (22). The methanolic polyester solution and the acid (sulfuric) are mixed and heated to 57–59°C. for about three hours. The polyvinyl alcohol precipitates, and the extent of hydrolysis is controlled by the time the polymer is allowed to stand before neutralization of the acid. The product is filtered, washed with methanol, and dried.

Alkaline Process (23). The methanolic polyester solution is mixed with a methanol solution of sodium or sodium methoxide and a rapid reaction takes place at room temperature, soon forming a gel. The extent of hydrolysis is controlled by the amount of sodium methoxide used and the temperature. The gel is broken up and the alkali neutralized by a low concentration of acetic acid in a solvent inert to the product (see Vol. 5, p. 820).

The resins are marketed under various names: Alvyl, Alvylol (Société Nobel française), Darex (Dewey and Almy Chem. Co.), Elvanol (Du Pont), Gelvatol (Shawinigan Chemicals Ltd.), Lemol (Bordon Co.), Polyviol (Wacker-Chemie GMBH), Resistoflex (Resistoflex Corp.), Rhodoviol (Société des Usines chimiques Rhône-Poulenc), Solva (Shawinigan Resins Corp.), Solvar (Shawinigan Chemicals Ltd.), Vinarol (Farbwerke Höchst AG), Vinavilol (Rhodiatoce S.p.A.), Vinol (Colton Chem. Co.).

Uses

Plasticized polyvinyl alcohol may be extruded or cast. However, in many of its applications polyvinyl alcohol is first placed in solution in water; this is done for example in inks and adhesives. Articles such as gloves may be formed by dip coating from solution.

Formation of Solutions. For low-acetate polyvinyl alcohol, a technique is used similar to that for gelatin. The powder is first thoroughly wetted by stirring in the cold, and then the temperature is raised slowly to 80–90°C. with continuous agitation, sufficient to prevent settling and balling of the solid. It gives a viscous, possibly slightly hazy mix which will remain in solution even at room temperature for some time. The medium-acetate products offer less difficulty, since they are soluble in water at room temperature. However, high-medium (over 35% acetate) and high-acetate products require the addition of some alcohol or acetone for solution.

Insolubilizing (2,10,16). In some applications insolubilizing treatments are given to the product after formation. In others, reagents are added to the solution to precipitate the polyvinyl alcohol.

Insolubilizing after-treatments may be done by heat-treating in the presence of salts such as copper-ammonia complex; by ferrous ferrocyanide; by dichromates in the presence of light; or by such organic reagents as sodium dibutylphenoldisulfonate (Aresklene 400), Congo red acid, *p*-(methylamino)phenol sulfate, resorcinol, and cinnamic aldehyde plus *p-tert*-amylphenol.

Polyvinyl alcohol may be precipitated from its aqueous solution by the addition

of 5–15% of many inorganic salts, or by borax, boric acid, and sulfonated phenols and their salts.

These insolubilizing treatments, and precipitation from solution, give products that, although not soluble in water, will gel and swell greatly in the presence of water.

A special application of insolubilized polyvinyl alcohol is the formation of fibers, insolubilized with formaldehyde. See Vol. **13**, p. 817.

Low-acetate grades of polyvinyl alcohol are used for extruded and cast articles such as gasoline hose, solvent-resistant gloves, films, and fibers; in inks; adhesives; sizes for paper and textiles; photographic and screen printing emulsions; polarizing film; release agents for use in molding polyester-resin glass-fiber compounds; semipermeable membranes and stencils; gaskets and belts; electrical and acoustic insulation; pharmaceuticals such as tablets, dressings, and sutures; boiler scale inhibitors (6); sausage casings and other food uses; cosmetics; emulsifiers; in ceramics to improve clay slips; and in paper coatings as binders for clay.

Medium-acetate grades are used in candy lacquers and confectionery; heat-seal coatings and remoistenable adhesives; sizes for nylon or cotton; cosmetics; emulsifiers; cold-water-soluble films; stencil screens; and parting agents for molding polyester resins.

High-acetate grades are used in solution or as a tape for adhesives; medicated films; and sizes for straw and felt.

Polyvinyl alcohol has also proved to be suitable for the preparation of mediums for the culture of bacteria and molds (7,10), and has been used in the synthesis of drying oil esters.

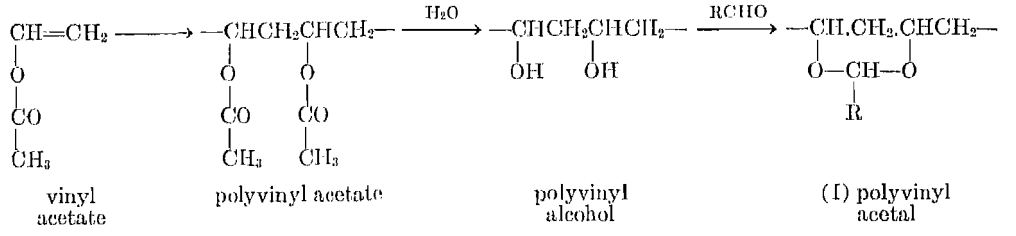
Bibliography for Polyvinyl Alcohol

(1) Blout, E. R., and Karplus, R., *J. Am. Chem. Soc.*, **70**, 862 (1948).
(2) *Elvanol*, 3rd printing, Du Pont, Wilmington, Del., 1953.
(3) Herrmann, W. O., and Haehnel, W., *Ber.*, **60**, 1658 (1927).
(4) Holzmüller, W., *Kunststoffe*, **30**, 177 (1940).
(5) Hueper, W. C., Landsberg, J. W., and Eskridge, L. C., *J. Pharmacol. Exptl. Therap.*, **70**, 201 (1940).
(6) Kainer, F., *Polyvinylalkohole*, Enke, Stuttgart, 1949.
(7) Marvel, C. S., and Denoon, C. E., Jr., *J. Am. Chem. Soc.*, **60**, 1045 (1938).
(8) Peierls, E. S., *Modern Plastics*, **18**, No. 6, 53 (1941).
(9) Platzer, N., *Modern Plastics*, **28**, No. 7, 95 (1951).
(10) Shawinigan Chemicals Ltd., unpublished data.
(11) Stark, W., Ph.D. Thesis, Freiburg, 1928.
(12) Staudinger, H., and Warth, H., *J. prakt. Chem.*, **155**, 261 (1940).
(13) Staudinger, H., Frey, K., and Starck, W., *Ber.*, **60**, 1782 (1927).
(14) Wagner, R. H., *Ind. Eng. Chem., Anal. Ed.*, **16**, 520 (1944).
(15) Can. Pat. 265,172 (Oct. 19, 1926), W. O. Herrmann and W. Haehnel (to Consort. f. elek. Ind.).
(16) Can. Pat. 446,175 (Jan. 13, 1948), A. H. Heatley and H. M. Collins (to Shawinigan Chemicals Ltd.).
(17) Ger. Pat. 450,286 (Oct. 5, 1927), W. Haehnel and W. O. Herrmann (to Consort. f. elek. Ind.).
(18) Ger. Pat. 588,762 (Nov. 27, 1933), W. Haehnel and W. O. Herrmann (to Consort. f. elek. Ind.).
(19) Ger. Pat. 643,650 (Apr. 14, 1937), H. Hopff (to I. G. Farbenind.).
(20) Ger. Pat. 667,863 (Nov. 22, 1938), W. Bauer (to Röhm & Haas.).
(21) U.S. Pat. 1,672,156 (June 5, 1928), W. O. Herrmann and W. Haehnel (to Consort f. elek. Ind.).
(22) U.S. Pat. 2,424,110 (July 15, 1947), G. O. Morrison and T. P. G. Shaw (to Shawinigan Chemicals Ltd.).
(23) U.S. Pat. 2,478,431 (Aug. 9, 1949), G. S. Stamatoff (to Du Pont).
(24) U.S. Pat. 2,643,994 (June 30, 1953), L. M. Germain (to Shawinigan Chemicals Ltd.).

T. P. G. SHAW AND L. M. GERMAIN

POLYVINYL ACETALS

The polyvinyl acetal-type resins are made from polyvinyl acetate by hydrolysis, followed by condensation with an aldehyde:



Acetal resins were first synthesized in Canada in 1928, where small-scale manufacture began in 1930. The formal and acetal are produced in Canada. Commercial production in the United States dates from 1936, where the butyral is produced in largest quantity because of its use in safety glass for automobiles. The formal is made by one U.S. manufacturer. The acetals are used to prepare molded articles, and for a variety of applications including adhesives, films, and coatings. See *Adhesives*; *Coated fabrics*; *Coatings, industrial*; *Textile technology*; *Varnishes*.

Properties. In addition to the type of aldehyde used, the properties of an acetal resin are affected by the chain length (or degree of polymerization) of the original polyvinyl acetate, the extent of hydrolysis, and the completeness of condensation with the aldehyde. Each chain of the polymer will have attached to it, in addition to the acetal groupings, some of the original acetyl groups, and a few free hydroxyl groups. It is convenient to express the results of analysis as per cent polyvinyl acetate content and per cent polyvinyl alcohol content by weight as though these were separate ingredients. Commercial acetal resins may contain 2–50% by weight of polyvinyl acetate and 5–30% by weight of polyvinyl alcohol, the remainder being polyvinyl acetal.

Assuming the same degree of polymerization of the polyvinyl acetate, and the same degrees of hydrolysis and acetalization, in the series of resins—formal, acetal, propional, and butyral—the formal will have the highest softening point, tensile strength, and viscosity in solution, as well as the lowest per cent elongation and range of solubility. As the series of resins with normal aliphatic aldehydes is continued, the flexibility and softness or tackiness of unplasticized films and the solubility in aliphatic hydrocarbons increase. For a given acetal resin, the softening temperature and tensile strength decrease with increasing degree of acetalization, while the solubility in water-immiscible solvents increases (5a,9,19,25). Solubility in solvents containing hydroxyl groups generally increases with increasing hydroxyl content. Cyclic carbonyl compounds, such as furfural and cyclohexanone, form resins with higher softening points than the products from open-chain compounds with the same number of carbon atoms.

Unstabilized films of the acetal resins deteriorate in direct sunlight if in contact with air. Thermosetting properties are imparted by curing or cross-linking under heat with a small quantity of a phenolic, alkyd, urea, or melamine resin.

Preparation. Preparing polyvinyl acetals involves hydrolysis of the polyvinyl acetate and acetalization of the resulting alcohol by condensation with the aldehyde (29). The preparation may be carried out in three different ways: (*1*) alkaline hydrolysis of the polyvinyl acetate in methanol or ethyl alcohol solution. This reaction is very rapid under anhydrous conditions; amounts of water up to 2–3% can be tolerated

at some expense of speed and catalyst exhaustion (see "Polyvinyl alcohol"). Hydrolysis is followed by acid condensation with the aldehyde as a separate step. (*2*) Acid hydrolysis of the polyvinyl acetate in acetic acid, dioxane, methanol, or alcohol-ester solvent followed by acid condensation with the aldehyde as a separate step. (*3*) Acid hydrolysis and acid condensation carried out simultaneously.

The acid catalysts used may be sulfuric, hydrochloric, phosphoric, benzenesulfonic, or other strong acid. Equimolar amounts of hydrochloric and sulfuric acids at a given temperature and under otherwise similar conditions give the same rate of hydrolysis; doubling the acid or raising the temperature 10°C. doubles the reaction rate. With phosphoric acid the rate is much slower. In acetic acid, at least 5–6% of the acetyl groups remain unchanged. Higher temperatures usually lead to a yellowish product. A higher proportion of water gives a higher percentage of hydroxyls and less color. Increasing the amount of aldehyde decreases the hydroxyl content. The apparent degree of polymerization may drop to nearly half during acid hydrolysis when using polyvinyl acetate of very high molecular weight, or only slightly when using that of low molecular weight, due to rupture of cross linkages between the chains. The resin is usually recovered as a precipitate after dilution with water. The product is then washed, stabilized with a trace of alkali or an organic amine, and dried.

Grades and Analysis. In one method of designating grades, the first figures are the approximate viscosities of the parent polyvinyl acetate (86 g. in 1000 ml. solution in benzene, measured in centipoises at 20°C.), while the remaining numbers indicate the extent of hydrolysis, that is, the percentage of the original acetyl groups that have been removed whether or not the resulting hydroxyl group is acetalized. Commercial acetal resins are usually made from polyvinyl acetates having a grade viscosity of 7 to 60.

Residual acetate groups are estimated by saponification with excess alkali, and hydroxyl groups by acetylation by means of acetic anhydride in pyridine. Acetal groups can be estimated by measuring the amount of free aldehyde released by distilling the resin with 50% aqueous phosphoric acid, but the results are generally somewhat low (19).

Health and Safety. The commercial acetal resins are nontoxic, and burn slowly. In compounding, the hazards of the other components should be taken into consideration.

Polyvinyl Formal

Polyvinyl formal [(I), R = H] (polyvinyl methylal, Formvar, Revyl F, Rhovinal F, Pioloform F, Mowital F), is available as a white or pale yellow granular powder. Commercial polyvinyl formals are soluble in acetic acid, aniline, chloroform, cresylic acid, dichlorodiethyl ether, dioxane, ethylene dibromide, ethylene dichloride, furfural, nitrobenzene, 1-nitropropane, pyridine, tetrachloroethane, and a 30/70 mixture of ethyl alcohol and toluene. The list of solvents is much greater for resins of higher acetate contents. As the acetate content of resins increases, the strength and rigidity as well as the inflection and heat distortion temperatures are lowered. Some representative commercial formals have sp.gr. 1.2, heat distortion point 88–93°C., tensile strength 10,000–11,000 p.s.i. See also references (6) and (24). Polyvinyl formal is resistant to dilute alkalies. Oxidative degradation at 150°C. or higher splits off formaldehyde and water (3).

Manufacture. Polyvinyl formal is usually prepared directly from polyvinyl

acetate dissolved in acetic acid, by heating at 70–80°C. in the presence of water, formaldehyde, and sulfuric acid (6). Heating is usually continued until about 92% of the acetyl groups have been hydrolyzed, and about 92% of the resulting hydroxyl groups in turn have been acetalized. The catalyst is neutralized by ammonium acetate, and the product after "disintegration" (precipitation in granular form in water) is washed and dried.

Uses. Polyvinyl formal (15/95) finds its main use in insulating enamel (Formvar wire enamel, Formex) and for coating magnet wire (6,15). The enamel is prepared from the formal in combination with an alkyl phenolic resin in a solvent mixture of cresylic acid or furfural and naphtha. Properties making the formal valuable in this application include its dielectric strength, toughness, adhesion, flexibility, and resistance to heat, abrasion, solvents, greases, and oils. Plasticized mixtures of the polyvinyl formal–phenolic resin are extruded for cable insulation. Polyvinyl formal is also used in separators for electric motor windings. Polyvinyl formal (7/70) solutions are used for bonding solenoid coils.

Granular polyvinyl formal placed between surfaces coated with a liquid phenol-formaldehyde resin provides, after application of heat and pressure, stronger metal-to-metal bonds than riveting or welding, as well as a marked saving of weight and labor in aircraft construction (11). The same adhesive system (Redux) is useful for gluing metal to wood, rubber, or thermosetting plastics. Special uses include the joining of brake and clutch linings and the manufacture of veneered aluminum. The formal has also been used as a binder in the manufacture of asbestos paper, in laminated shoe soles, and for stiffening collars. Emulsions may be prepared for laminating and impregnating (10). In Great Britain during World War II the formal was used for bonding and coating birch veneers (Hydulignum) for airplane propellers in regions where metal propellers suffered sand abrasion (1).

Polyvinyl formal is an ingredient in high-grade varnishes. It is also used for coating paper and artificial leather, and in wood sealers, and has proved suitable for coating photographic flash-bulbs to prevent shattering. Mixed with phenolics, the formal provides adhesion, toughness, and hardness in drum, tank, and food-can linings. Corrosion-resistant steel priming compositions may be based on the formal (13).

Molding compositions containing polyvinyl formal have exceptional strength, toughness, and dimensional stability in such uses as machine parts, tool handles, nonmarring hammerheads, nonbreakable phonograph records, combs, and spectacle frames. Formal compounds may be extruded at 320–380°F. Extruded tubing is suitable for gasoline, oil, and aromatic fuel lines. Injection molding compositions require 350–450°F., 20,000–35,000 p.s.i., and relatively large gates. Molded articles have a very hard surface, abrasion resistance, rigidity, and machinability.

Gasoline-resistant diaphragms are made from cured mixtures of polyvinyl formal and a diisocyanate-modified polyester-amide (Vulcaprene A); leather cloths of the same mixture have high abrasion and flex resistance and are nonthermoplastic (8).

A water solution of polyvinyl alcohol may be foamed with air in the presence of a wetting agent, inorganic acid, and formaldehyde to produce the strongest known material for its weight, of interest in thermal insulation and as a substitute for balsa wood. Polyvinyl formal household sponges (Ivalon) are tough, resilient, and soft (40). Fibers of polyvinyl alcohol, spun from water solution and treated with formaldehyde, as developed in Japan (Vinylon, Kuravilon, Kuralon, Kaneviyan, Gosei-Ichigo), have good strength, abrasion resistance, and heat retention (22,37).

Polyvinyl formal films are used as a mounting medium and for preparing surface replicas in electron microscopy. Replicas of snowflakes are made from 1% ethylene dichloride solutions. Films with 5% titanium dioxide serve as dialyzing membranes (39).

Polyvinyl Acetal

Polyvinyl acetal [(I),R = CH_3], although the name is used to designate the general class of acetal resins, specifically designates the resin made with acetaldehyde (Alvar, Revyl A, Rhovinal A). Commercial polyvinyl acetals have a slightly yellow color. These resins are soluble in acetic acid, acetone and higher ketones, amyl acetate, aniline, benzene, *n*-butyl acetate, *n*-butyl butyrate, chloroform, cyclohexanone, 1,2-dichloroethane, dioxane, ethyl acetate, ethyl alcohol, isobutyl acetate, isopropyl acetate, methanol, methyl acetate, nitrobenzene, paraldehyde, pyridine, tetrachloroethane, toluene, and trichloroethylene. Polyvinyl acetals have a tensile strength of 6000–10,000 p.s.i., heat distortion temperatures of 65–90°C., and a dielectric strength of 950 volts/mil.

Manufacture. In Canada, the acetal is made directly from polyvinyl acetate dissolved in a *n*-butyl alcohol–*n*-butyl acetate mixture, by heating with water, paraldehyde, $O.CH(CH_3).O.CH(CH_3).O.CHCH_3$, and sulfuric acid. After neutralization with sodium acetate, the alcohol-ester solvent is removed by steam distillation and washing, and the product is shredded and dried (14). Standard grades are 7/70 and 15/70.

At Höchst, Germany, to make the acetal, polyvinyl alcohol was first prepared by heating a 40% solution of polyvinyl acetate in methanol–methyl acetate (60:40) at 50–55°C. for about 3 minutes using sodium hydroxide in methanol as catalyst (4,5,19). The solvent was boiled off, and water added to produce an 8% solution of polyvinyl alcohol. After filtration, acetaldehyde was added (140% of the theoretical amount required) with 2% of hydrochloric acid; the mixture was reacted at 10–12°C., and finally at 40°C. The product, after cooling, dilution, filtering, and washing, was plasticized and sheeted for safety glass.

Uses. Polyvinyl acetal is useful in spirit-soluble lacquers, giving hard, tough, and abrasion-resistant films, which are applied by brush or spraying. As an ingredient in nitrocellulose lacquers, the acetal imparts improved durability and gloss retention. Similar uses include lacquers with modified linseed oil, lacquers for electrical apparatus, varnishes, and shellac substitutes.

Plasticized or modified acetal solutions give high-strength bonds between porous or nonporous surfaces. The flexibility of acetal adhesives makes them suitable as belting cements. Special applications include laminated products, wood glues, china cements, abrasive-wheel bonding agents, insulating tapes, and washable adhesive bandages.

Acetal solutions increase the transparency and grease resistance of wrapping papers and provide gloss coatings for fabrics, paper, and artificial leather. Impregnating dopes are used in treating or sizing fabrics, felt, and paper. The acetal produces tough transparent films. Disintegration of archeological specimens such as bones, pottery, and textiles is halted by a thin 7/70 film, applied by immersion in a solution.

Acetal emulsions may be used as a sealing coat for porous surfaces under cellulose lacquers or other coatings, as a flexible pigment finish for leather, which is resistant to

water and abrasion, and as a pigmented finish to impart water resistance to felt. The emulsions are also useful as adhesives and bonding materials for woven fabric or leather, and have been used as extenders for rubber latex in the manufacture of leather board from scrap leather, and as a substitute for rubber latex in the boot and shoe industry (10).

Injection molding of acetal powders is done at 340–375 °F., compression molding at 212–265 °F. Molded articles include sound-recording disks, dentures, shoe heels, buttons, printing plates, parts for electrical apparatus, toothbrush handles, spectacle frames, wall tiles, dishes, trays, and novelties.

In Germany, the acetal was used in lacquers, for stiffening straw hats and sizing felt hats, as well as in safety glass and textile sizing.

Polyvinyl Butyral

Polyvinyl butyral [(I),R = $CH_3CH_2CH_2$] (Bakelite XYHL and XYSG, Butacite, Butvar, Flexseal, Saflex, Vinal, Revyl B, Rhovinal B, Mowital B, Pioloform B) is the most important of the acetal resins in the U.S., being the standard interlayer material in safety glass. Annual U.S. production in 1953 has been estimated at 15–20 million pounds (12). Cost in 1953 was about $1/lb.

Polyvinyl butyrals are generally soluble in esters, alcohols, glycol ethers, ketones, dioxane, and chlorinated and aromatic hydrocarbons, and are insoluble in aliphatic hydrocarbons and mineral oils. An unplasticized rigid sheet of butyral has a specific gravity of 1.07–1.20, a heat distortion point of 115–140 °F., a dielectric strength of 420–440 volts/mil, an impact strength, Charpy, notched, of 2.5–9.0 ft.-lb./in., and a tensile strength of 4000–8500 p.s.i. (1,18,19). Data on cross-linked or thermosetting butyrals have also been published (1,20,23).

Polyvinyl butyral for safety glass should contain 19–20% polyvinyl alcohol, equal to an acetal reaction of about 70% and less than 3% polyvinyl acetate by weight. The free hydroxyl groups are essential for good bonding. Polyvinyl butyral plasticized for safety glass has a specific gravity of about 1.07, n_D^{25} 1.48, a tensile strength of 1980–2900 p.s.i., and an elongation at failure of 300% (1,18). For molding purposes, higher acetal reactions of up to 85% are usual to decrease the water sensitivity, increase the compatibility with plasticizers and modifying resins, and increase the low-temperature flexibility.

Manufacture. Polyvinyl acetate is dissolved in an alcohol-ester mixture or other solvent, hydrolyzed with an alkaline or acid catalyst, and later acetalized with butyraldehyde in the presence of an acid catalyst. Because of the importance of product clarity, the polyvinyl acetate solution is filtered before reaction, and the product is precipitated by water and carefully washed (5,19,23,30).

Uses. Plasticized polyvinyl butyral has proved outstanding as the interlayer for *safety glass* (laminated glass) because of its crystal-clear transparency, stability to light and heat, adhesion to glass, moisture resistance, impact resistance, and its toughness, resilience, and flexibility over a wide temperature range. The interlayer sheeting is bonded between glass by heat and pressure, with or without the use of an intermediate adhesive (23). It is also used between sheets of polymethyl methacrylate, and as an inside lacquer for window glass, to render them nonshattering.

During World War II the plasticized butyral (Heydenite X, Horco X, Saflex TS), cured or cross-linked with a urea-formaldehyde, phenol-formaldehyde, or other resin,

proved to be superior to natural rubber as a flexible waterproof cloth coating for raincoats and ponchos; gas-impermeable fabrics; tents; tarpaulins; groundsheets; hospital sheeting; hammocks; air mattresses and sleeping bags; water, food, and clothing bags; life preservers and rafts; emergency sails; and collapsible boats and pontoons (1,17,20). During the rubber shortage, the butyral was also used for shoe heels, while cotton duck impregnated with butyral plasticized with triethylene glycol di(2-ethylbutyrate) (Flexol 3GH) or triethylene glycol di(2-ethylhexanoate) (Flexol 3GO) and then calendered and laminated, was found to be a satisfactory leather replacement for shoe soles (7). For fabric coating the butyral may be applied by calendering or by knife-coating solutions. A fabric treated with polyvinyl butyral becomes resistant to heat, abrasion and wear, water, solvents, and stains, while retaining its flexibility, appearance, and softness or feel (21). Butyral-coated fabrics are used in fine upholstery, drapery, table cloths, luggage, raincoats, and scuff-resistant panels. Treatment of nylon, as in parachute webbing, with an aqueous dispersion (Merlon BR), improves its resistance to abrasion and ultraviolet light (26).

A wash primer type of metal conditioner with polyvinyl butyral, chromate pigment, solvent, and phosphoric acid as passivating agent has excellent adhesion to clean metal surfaces and air-dries rapidly to leave a uniform protective film to which most paints and coatings will adhere (2,38). A butyral wash primer under a topcoat of polyvinyl chloride-acetate copolymer with rosin and cuprous oxide prevents metal corrosion under exposed edges of the paint film in salt water (2,16). Aluminum sheets prime-coated with the butyral are protected from corrosion during subsequent light drawing and forming. Butyral wash primers have found wide application in marine coatings, as well as for pipelines, oil storage tanks, and air-conditioning equipment.

A concentrated alcohol solution of the butyral may be emulsified with water and sprayed on cloth articles as an undercoat for nitrocellulose lacquers, resulting in greater flexibility and adhesion to the cloth. The butyral with hydrolyzed ethyl silicate gives a coating for glass brick (35). The butyral serves in primers for house paints and enamels. Phenolic-butyral formulations give durable wood finishes and knot-sealers for pine lumber (2). The butyral is used to moistureproof regenerated cellulose films and in heat-sealable coatings with nitrocellulose. Butyral coatings are used for can and gasoline-tank linings. Unplasticized butyral is used to coat metal foil for wrapping foods. A butyral coating improves the adhesion of inks and adhesives to aluminum foil. Coatings and lacquers for paper, resins, glass, wood, and leather are also provided. The butyral is used for waterproofing felt, and in impregnating compositions.

Butyral solutions may be used to cast films and to prepare dipped articles. Butyral films are suitable for waterproof packaging. Soft and hard sponges may be prepared from the butyral. A mixture of the butyral with the copolymer of methyl methacrylate and vinyl acetate may be used to form sheets or as a molding powder (32).

Butyral adhesives give tough, flexible, and shock-resistant bonds; various applications include bonding mica, laminating cloth, leather adhesives, and pressure-sensitive tapes. Polyvinyl butyral–phenolic adhesives will cement almost any surface to metals or thermosetting resins, and will bond grease-free metals under heat and light pressure (2). Butyral-modified phenolic adhesives have increased tensile and impact strengths in bonding plywood. Hot melts based on the butyral are used in high-speed book binding.

Extruded articles include flexible tubing and hose for fuel and oil lines. Com-

pression molding is done at about 275°F. and 1000–2000 p.s.i., injection molding at about 400°F. and 11,000–15,000 p.s.i. Molded products are tough and shock resistant.

Gaskets or sealing rings for food containers are cut from butyral sheeting plasticized with di-*n*-butyl sebacate (34). Golf-ball covers may be made from crepe rubber, polyvinyl butyral with di-*n*-butyl phthalate, and titanium oxide (33).

Other Acetal Resins

In the laboratory polyvinyl alcohol has been condensed with numerous other aldehydes, as well as with mixtures of aldehydes (forming "co-acetals") and with ketones (forming "ketals") (23), but only a few of these have been prepared commercially. The co-acetal of acetaldehyde and butyraldehyde (Revyl AB) is produced in France. In Germany, Pioloform AZ15 Sp 40M was a co-acetal prepared from equal amounts by weight of acetaldehyde and diethylacetaldehyde (2-ethylbutyraldehyde) (5), while the ketal made from polyvinyl alcohol and cyclohexanone (Mowital O) was used for coating wires. An ethylene–vinyl acetate copolymer may be hydrolyzed and reacted with aldehydes to produce tough flexible films (36). Acetal resins have also been prepared from copolymers of vinyl acetate with methyl acrylate (27,31), methyl methacrylate (28), dimethyl maleate, or ethyl crotonate (31).

Bibliography for Polyvinyl Acetals

(1) Akin, R. B., *Chem. Inds.*, **52**, 456–60, 599–603 (1943).
(2) Bakelite Corp., *Vinylite Vinyl Butyral Resins*, N.Y., 1949; summarized in *Chem. Age (London)*, **62**, 889–90 (1950).
(3) Beachell, H. C., Fotis, P., and Hucks, J., *J. Polymer Sci.*, **7**, 353–76 (1951).
(4) DeBell, J. M., Goggin, W. C., and Gloor, W. E., *German Plastics Practice*, DeBell and Richardson, Springfield, Mass., 1946, ch. 5.
(5) Dunlop, R. D., *F.I.A.T. Final Rept.*, No. **1109** (1947).
(5a) Fitzhugh, A. F., and Crozier, R. N., *J. Polymer Sci.*, **8**, 225–41 (1952); **9**, 96 (1952).
(6) Fitzhugh, A. F., Lavin, E., and Morrison, G. O., *J. Electrochem. Soc.*, **100**, 351–5 (1953).
(7) Gallay, W., *J. Am. Leather Chem. Assoc.*, **38**, 250–55 (1943); *Can. Chem. Process Inds.*, **27**, 551–54 (1943).
(8) Harper, D. A., Smith, W. F., and White, H. G., *Proc. 2nd Rubber Technol. Conf. (London)*, **1948**, 61–68.
(9) Kamp, F., *Chim. peintures*, **14**, 442–45 (1951).
(10) Mayne, J. E. O., *Trans. Inst. Rubber Ind.*, **19**, 196–200 (1944).
(11) Meakin, K. S., *Research (London)*, **5**, 126–32 (1952).
(12) *Modern Plastics*, **31**, No. 1, 103–5, 185–93, 198, 200 (1953).
(13) Monsanto Chemical Co., Plastics Division, *Resin F-770* (Data Sheet), Springfield, Mass., 1950.
(14) Mueller, W. H., *Can. Chem. Process Inds.*, **29**, 395–97 (1945).
(15) Patnode, W., Flynn, E. J., and Weh, J. A., *Ind. Eng. Chem.*, **31**, 1063–71, 1224 (1939).
(16) Patton, C. W., *Offic. Dig. Federation Paint & Varnish Production Clubs*, No. **278**, 267–279 (1948); *C.A.*, **42**, 4368h.
(17) Plastics Catalogue Corp., *Plastics Catalog*, N.Y., 1944, pp. 84–85, 213–14, 891–95.
(18) Plastics Materials Manufacturers' Association, *Technical Data on Plastic Materials*, Washington, D.C., 1943.
(19) Platzer, N., *Modern Plastics*, **28**, No. 10, 142, 144, 146, 148 (1951).
(20) Plumb, D. S., *Ind. Eng. Chem.*, **36**, 1035–38 (1944).
(21) Plumb, D. S., *India Rubber World*, **112**, 744–45 (1945); **122**, 62–64 (1950); *Plastics (Chicago)*, **6**, No. 1, 80–81, 94 (1947); *Am. Dyestuff Reptr.*, **36**, No. 12, P332–34 (1947); *Textile Age*, **11**, No. 10, 64, 66, 68–69 (1947).
(22) *Office Tech. Services Rept.*, **PB** L-88,980, **PB** 100,358.

(23) Schildknecht, C. E., *Vinyl and Related Polymers*, Wiley, N.Y., 1952, pp. 323–85.
(24) Shawinigan Products Corp., *Formvar*, N.Y., 1954.
(25) Weihe, A., *Kunststoffe*, **31**, 52–5 (1941).
(26) Willis, C. A., *CADO Tech. Data Dig.*, **14**, No. 15, 15–25 (1949); *C.A.*, **43**, 8142g.
(27) Brit. Pat. 477,885 (Jan. 7, 1938), Shawinigan Chemicals Ltd.
(28) Brit. Pat. 578,767 (July 11, 1946), Imperial Chemical Industries Ltd.
(29) U.S. re. 20,430 (June 29, 1937), G. O. Morrison, F. W. Skirrow, and K. G. Blaikie (to Canadian Electro Products Co.). Reissue of 2,036,092.
(30) U.S. Pat. 2,162,678 (June 13, 1939), H. F. Robertson (to Carbide & Carbon Chemicals Corp.).
(31) U.S. Pat. 2,229,781 (Jan. 28, 1941), A. Weihe and A. Voss (to General Aniline & Film Corp.).
(32) U.S. Pat. 2,326,543 (Aug. 10, 1943), M. L. Macht (to Du Pont).
(33) U.S. Pat. 2,362,961 (Nov. 14, 1944), W. E. Welch (to Monsanto Chemical Co.).
(34) U.S. Pat. 2,375,388 (May 8, 1945), J. D. Ryan (to Libbey-Owens-Ford Glass Co.).
(35) U.S. Pat. 2,385,921 (Oct. 2, 1945), J. W. Jordan (to Pittsburgh Corning Corp.).
(36) U.S. Pat. 2,396,209 (March 5, 1946), W. H. Sharkey (to Du Pont).
(37) U.S. Pat. 2,487,864 (Nov. 15, 1949), C. W. Gayler (to American Viscose Corp.).
(38) U.S. Pat. 2,525,107 (Oct. 10, 1950), L. R. Whiting and P. F. Wangner, Jr. (to U.S.A., Secy. of the Navy).
(39) U.S. Pat. 2,563,644 (Aug. 7, 1951), N. Drisch and P. Herrbach (to Comptoir des Textiles Artificiels).
(40) U.S. Pat. 2,609,347 (Sept. 2, 1952), C. L. Wilson; see also *Chem. Inds.*, **64**, 378–79 (1949).

K. G. Blaikie and M. S. W. Small

VINYL CHLORIDE

Vinyl chloride at room temperature and atmospheric pressure is a colorless, inflammable gas with a pleasant ethereal odor. It is a colorless mobile liquid below −13.9°C. It was first prepared by Regnault (6) from the reaction of ethylene dichloride and an alcoholic solution of potassium hydroxide:

$$CH_2Cl{-}CH_2Cl + KOH \xrightarrow{CH_3OH} CH_2{=}CHCl + KCl + H_2O$$

However, alkaline treatment of ethylene dichloride is not used industrially since half of the chlorine from the ethylene dichloride is converted to salt.

Since the 1930's vinyl chloride polymers and copolymers have grown from pilot-plant stage to an industry producing over 500 millions of pounds per year. This rapid increase is the result of unique properties of the vinyls in which they can be varied from soft rubbery products with good tensile and elongation properties to rigid products with high structural modulus and excellent impact resistance. Such a wide variation in hardness, together with such other important properties as chemical, oxidation,

TABLE I. Sales of Polyvinyl Chloride and Copolymer Resins (50% or More Polyvinyl Chloride) in 1954.

Use	Pounds
Film (resin content)	63,860,000
Sheeting (resin content)	57,868,000
Molding and extrusion (resin content)	147,284,000
Textile and paper treating and coating (resin content)[a]	49,546,000
Flooring (resin content)	34,885,000
Protective coatings (resin content)	23,676,000
All other uses (resin content)	34,447,000
Total	*411,566,000*

[a] Includes data for spreader and calender-type resins.

and ozone resistance, excellent dielectric strength, fireproofness, and ease of processing, have made their use possible in a broad range of industrial applications. Calendering, extrusion, and molding applications were first developed and more recently casting and coating techniques based on plastisols, organosols, and latexes have been developed. These formulations were made possible by the development of new forms of resin.

Sales of these resins in 1954 are shown in Table I (U.S. Tariff Commission). By comparison, 1954 sales of all other vinyl resins amounted to 101 million pounds.

TABLE II. Properties of Vinyl Chloride.

B.p. at 760 mm.	−13.81°C.
F.p.	−153.77°C.
Flash point, COC.	−78°C.
Explosive limits in air.	4-22% by vol.
Liquid density at −20°C, g./ml.	0.98343
Density change with temperature between −30°C. and −20°C. g./ml./°C.	Approx. 0.00164
Viscosity, cps.	
At −10°C.	0.248
At −20°C.	0.274
At −30°C.	0.303
At −40°C.	0.340
Surface tension, dyne/cm.	
At −10°C.	20.88
At −20°C.	22.27
At −30°C.	23.87
n_D^{15}	1.398 calc.
Vapor pressure, mm. Hg	
At 25°C.	2,660
At −13.37°C.	760
At t_e − 15.76°C[a]	692
At −55.8°C.	100
At −73.9°C.	30
At −87.5°C.	10
At −109.4°C.	1
Specific heat of liquid, cal./g./°C.	0.38
Specific heat of vapor at C_p and 25°C., cal./g. mole/°C.	12.83
$\gamma = C_p/C_v$	1.183
Latent heat of vaporization, cal./g.	
At 25°C.	71.26
At −13.37°C.	79.53
Latent heat of fusion, cal./g.	18.14
Heat of formation (est.), cal./g.	−120
Heat of polymerization (est.), cal./g. (8)	−272
Critical temperature, T_c	156.5°C.
Critical pressure, P_c, atm.	55.2
Critical volume, V_c, ml./g.	2.70
Volumetric shrinkage upon polymerization	Approx. 35%
PV/RT	
At 156.5°C.	0.264
At 25°C.	0.9178
At −13.37°C.	0.9640
At t_e − 15.76°C[a]	0.9652
At −73.90°C. (30 mm. Hg)	1.000
Dielectric constant at frequency of 10^6 and 17.2°C.	6.26

[a] t_e = temperature at which a mole of vapor in equilibrium with the liquid occupies 22.414 liters.

Properties (10)

Vinyl chloride is soluble in carbon tetrachloride, ether, ethyl alcohol, and most organic solvents. The solubility of water in vinyl chloride is 0.11%. Vinyl chloride is noncorrosive when dry at atmospheric temperatures. Acetylene impurities in commercial vinyl chloride react with copper. The commercial product has a faint phenolic odor due to the inhibitor. Other properties of vinyl chloride are given in Table II.

Chemical Reactions. Vinyl chloride contains two functional groups, the chlorine and the double bond. The chlorine atom, as with all such halogen atoms attached to a double-bonded carbon, is quite unreactive as compared to the halogen of the corresponding saturated alkyl halide. This inert character is so pronounced that vinyl chloride will not react with magnesium to form a Grignard reagent. It is because of this inertness that vinyl chloride can be made by the elimination of only one molecule of hydrogen chloride from 1,2-dichlorethane (3). Vinyl chloride is so resistant to further reaction by cracking or hydrolysis that there is no difficulty in preventing the elimination of another molecule of hydrogen chloride to form acetylene. The reactions of the double bond are normal, and one of the more interesting from the monomer point of view is:

$$CH_2{=}CHCl \xrightarrow{Cl_2} CH_2Cl{-}CHCl_2$$

Subsequent dehydrohalogenation of the 1,1,2-trichlorethane by cracking or by alcoholic caustic results in the formation of vinylidene chloride, another important vinyl monomer:

$$CH_2Cl{-}CHCl_2 \xrightarrow[\text{alcoholic NaOH}]{\text{cracking or}} CH_2{=}CCl_2 + HCl$$

In either method of dehydrohalogenation, it is the carbon containing the single chlorine atom which yields its halogen.

Manufacture

Two methods are currently used in industry: (1) the reaction of acetylene and hydrogen chloride in the presence of a mercuric catalyst:

$$CH{\equiv}CH + HCl \xrightarrow{HgCl_2} CH_2{=}CHCl \qquad (1)$$

and (2) the cracking of ethylene dichloride:

$$CH_2Cl{-}CH_2Cl \xrightarrow[\text{contact catalyst}]{300\text{–}600^\circ C.} CH_2{=}CHCl + HCl \qquad (2)$$

Vapor Phase Catalytic Reaction of Acetylene and Hydrogen Chloride. This process is widely used in both Germany and the U.S.: Acetylene is passed through an acid or caustic scrubber to dry the gas and remove trace impurities, such as ammonia, hydrogen sulfide, phosphine, and arsine, normally present. This purified gas is then mixed with anhydrous hydrogen chloride in an approximately equivalent molar ratio and passed into steel tubes containing a catalyst. Since the reaction is exothermic (22.8 kcal./mole), the tubes, maintained at a temperature between 160 and 250°C., are cooled to remove heat. The reacted gases contain, in addition to the vinyl chloride, unreacted acetylene, hydrogen chloride, and higher chlorine-containing

compounds such as 1,1-dichloroethane. These impurities are removed by scrubbing with aqueous caustic, and the monomer is further purified by distillation.

Vapor Phase Cracking of Ethylene Dichloride (12,33,36). This process is similar to the above and involves the passing of 1,2-dichloroethane over contact catalysts, such as pumice or charcoal, at temperatures of 200–350 °C. The by-product hydrogen chloride is separated from the vinyl chloride by distillation. To improve efficiency, the hydrogen chloride, after purification, is then supplied to process (1) with acetylene to produce additional vinyl chloride.

Shipment and Safety, Stabilization. Although vinyl chloride does not polymerize except in the presence of free-radical catalysts or actinic radiation, it is normally stabilized for storage and shipment by the use of such materials as phenol, *tert*butyl catechol, and hydroquinone in concentrations varying from 50 to 500 p.p.m. (In Germany liquid vinyl chloride has been transported in pressure tank cars without stabilizer.) The stabilizer is removed before polymerization by scrubbing with caustic or by distillation.

Vinyl chloride is relatively nontoxic. The presently accepted maximum allowable concentration for an eight-hour exposure is 500 p.p.m. (11). Explosions and fires from vinyl chloride–air mixtures are the major hazards. The limits of flammability are 4–22% by volume in air. Vinyl chloride does not form peroxides by autooxidation as readily as other monomers such as butadiene; however, ICC approved cylinders and tank cars have pressure relief devices. Maximum filling density is 84% for cylinders and 87% for tank cars for Class ICC-105 A (11).

Polymerization

Ostromislensky (5) in 1912 reported that he had obtained resin products from the polymerization of vinyl bromide catalyzed by sunlight. He observed that the polymers so produced varied greatly in their solubility, and he arbitrarily classified them into groups which he defined as α, β, and γ isomers. These classifications were based on the relative rates of solubility of the polymer in such solvents as chlorobenzene, ethylene dichloride, and carbon disulfide, the γ isomer being insoluble in these solvents. This type of polymer was currently adjudged to have the greatest commercial promise and was given the name "Kauprenbromid." When heated at 130 °C., polyvinyl bromide was observed to carbonize, liberating hydrogen bromide copiously. Ostromislensky then found that he could remove bromine from the polymer by treatment with zinc dust suspended in absolute alcohol to give a product which he mistakenly thought might be a polyene hydrocarbon.

Klatte and Rollett (15) reported five years later that they had obtained polymers of vinyl chloride by means of peroxides rather than the sunlight catalysis of Ostromislensky. Plansen (19) found that a polymer was formed directly when dry acetylene and hydrogen chloride were heated under pressure at 150–200 °C. It was indicated by all the early investigators that lower temperatures of polymerization were necessary to give polymers with the highest molecular weight and greatest stability. Semon (21) in 1927 found that the "insoluble" γ polymer of Ostromislensky could be dissolved by a number of high-boiling solvents, such as *o*-nitrodiphenyl ether and tricresyl phosphate, when heated to elevated temperatures. On cooling, these dough-like mixtures became rubbery gels. It was the rubber-like plastic made possible by the combination of vinyl chloride polymers and plasticizers that gave commercial impetus to an otherwise laboratory curiosity.

Solution Polymerization of Vinyl Chloride. Much of the early work was concerned with bulk polymerization of vinyl chloride. Ostromislensky had noted that oxygen retarded photopolymerization, but not until 1937 was it demonstrated by Schoenfeld (26) that a faster polymerization and a more stable polymer could be obtained by the use of an inert atmosphere such as nitrogen or carbon dioxide.

Bulk polymerizations were not feasible on a commercial scale since solid, horny masses resulted if the polymerizations were permitted to go to completion. Conversions of greater than 25% frequently became too viscous to permit adequate heat removal. The use of special solvents such as

acetone, as reported by Downes (29), made possible the use of hydrogen peroxide (insoluble in vinyl chloride) as a catalyst, and also increased conversion without attendant danger of the charge becoming solid. Douglas (25) developed a continuous homogeneous polymerization technique in which the polymer in suspension in the monomer was withdrawn from the reactor and filtered off under pressure, the monomer being recycled. Temperatures of polymerization were reported ranging from 30 to 45 °C. with pressures varying from 60 to 120 p.s.i. Equipment used was usually lead- or glass-lined stirred autoclaves with jackets for cooling.

Suspension Polymerization. The most widely used polymerization technique for vinyl chloride involves water as a medium with a suspension agent such as polyvinyl alcohol and an oil-soluble catalyst such as benzoyl peroxide. A typical recipe reported to have been used at the Burghausen plant of Wacker (1) was: 100.0 parts vinyl chloride, 0.1–0.2 part benzoyl peroxide, 200.0 parts water, 0.05–0.1 part polyvinyl alcohol.

The ratio of monomer to water can be varied over a wide range, the limiting factor being sufficient fluidity of the final polymer-water slurry to permit adequate dissipation of the heat evolved during polymerization. Particle size has been controlled to give a granular polymer for better filtering and drying. Commercial suspension resins show little or no retention on a 100-mesh (U.S. Standard) screen and from 30 to 80% retention on a 200-mesh screen. Such a particle size is achieved by rapid agitation in lead- or glass-lined autoclaves at temperatures ranging from 35 to 45 °C. To prevent a pH drop (HCl formation) during polymerization, various alkaline buffers have been used, such as sodium carbonate, bicarbonate, and phosphate, to maintain the pH at 5–8 (14). Polymerization under inert atmospheres such as nitrogen (26) not only increases reaction rate, but also reduces the HCl evolved during polymerization, thereby increasing the stability of the polymer.

Oil-soluble catalysts such as dibenzoyl peroxide, acetyl benzoyl peroxide, or dibutyryl peroxide are preferred to the water-soluble persulfate catalysts in suspension or "pearl" type polymerizations since the latter, in addition to being slower, produce particles of too fine a particle size to be handled in conventional filtering and drying equipment. More recently there have been introduced suspension resins with increased surface area. These resins absorb plasticizer more rapidly and are referred to as powder mixing or "easy processing" resins. Their use permits a much faster processing cycle and in some instances extrusion is carried out from dry resin-plasticizer blends.

There is little published information regarding molecular weight distribution, branch chaining, etc., of vinyl chloride polymers; however, Mark reports that vinyl chloride polymers in general have comparatively narrow molecular distributions, especially as compared with polystyrene. Specific viscosities of commercial vinyl chloride polymers range from 0.3 to 0.5 (A.S.T.M. D1243–52T). Molecular weight is usually controlled by the temperature maintained during polymerization, and to a lesser degree by chain-modifying or -terminating agents.

Emulsion Polymerization. Emulsion polymerization techniques are employed to give a particle size range sufficiently small to remain in colloidal suspension. The more permanent of these are regarded as latexes. Such polymerization systems are usually based on water-soluble catalysts, such as sodium peroxysulfate, and micelle-forming agents, such as sodium laurylsulfate or sodium alkylbenzenesulfonate. To produce stable latexes with high solids, a method has been described by Powers (35) for controlling particle size by the use of seed latex and restricting the effective concentration of emulsifier. Stable latexes have been produced ranging in solids content from 50 to 56%. The pH of such systems is usually maintained between 6 and 8.

Low pH systems ranging from 2 to 3 have been reported but are generally less stable and are not offered for commercial sale.

Coagulation and drying of finely divided particle systems are more difficult than for suspension polymers; however, this is the source of the rapidly growing plastisol and organosol resins used in coating and casting applications. Careful control of particle size is necessary to produce resins which will give plasticizer dispersions with optimum rheological properties.

Copolymerization

Vinyl Chloride–Vinyl Acetate. Research in the field of vinyl chloride–vinyl acetate copolymers was predicated on the belief that certain limitations, such as insolubility and difficult processability, of vinyl chloride polymers would prevent their wide commercial acceptance. Carbide & Carbon Chemicals Corp. did much of the basic research and development on vinyl chloride–vinyl acetate systems that ultimately resulted in their Vinylite resin series.

In 1928 Reid (23) first described a copolymer based on 22 parts vinyl chloride, 25 parts vinyl acetate, 3 parts acetaldehyde, and 50 parts solvent. In a later patent Reid (24) describes in clearer detail a method involving the use of a solvent in which the monomers were soluble, but in which the polymer would be insoluble when the desired molecular weight had been obtained. Such a system is illustrated in which an 80/20 mixture of vinyl chloride–vinyl acetate was polymerized in an equal weight of hexane. The reaction was catalyzed with benzoyl peroxide, 0.5% on the monomers, and was carried out in a lead-lined, stirred autoclave at 40°C. over a period of 60 hours. The product, after filtering and drying, was a low-density white powder which was soluble in toluene only to the extent of 12%.

Increased polymerization rates were obtained by Shriver (22) from the use of acetyl–benzoyl peroxide as a replacement for benzoyl peroxide. Lower catalyst concentrations, ¼ to ½ that for benzoyl peroxide, and lower temperatures could be employed to give a faster reaction rate. These modifications contributed to increased stability of the polymer. The use of tetraethyl lead (20) was reported as a polymerization catalyst. However, the use of lead compounds as stabilizers has developed into more commercial importance than their use as catalysts.

One of the first techniques for continuous polymerization was described by Douglas (25) in which the vinyl chloride–vinyl acetate mixture was dissolved in butane. The polymer could be separated from the low-boiling solvent from which it precipitated during polymerization, giving a product which could be used directly and without further heat incidental to drying.

The effect of molecular-weight distribution and composition was studied by Douglas and Stoops (2), who found that they could separate a polymer into its various molecular-weight components by fractional precipitation from solution. They observed further that the physical properties of the various fractions varied directly with molecular weight, but that the change was most pronounced at a molecular range below 8000 (see Table III).

Adhesive resins have been made by incorporating carboxyl-containing monomers and partially hydrolyzed polymers in which hydroxyl groups are present (see "Polyvinyl alcohol"). Vinylite VMCH is described as an 86/13/1 vinyl chloride–vinyl acetate–maleic anhydride interpolymer. Vinylite VAGH is a partially hydrolyzed

TABLE III. Physical Properties of Vinyl Chloride–Vinyl Acetate Interpolymer Fractions.[a]

Molecular weight	15,800	14,600	13,200	11,100	7,500	5,800
Brinell hardness (2.5-kg. load)	13.9	13.5	12.3	12.7	12.2	—
Viscosity, cps., 20% in methyl isobutyl ketone	Gel	Gel	370	145	45	24
Plasticity at 120°C. (Scott)	39	52	66	82	94	—
Tensile strength, p.s.i.	9,955	9,745	9,630	9,180	6,680	1,120
Impact strength, ft.-lb.	0.36	0.33	0.32	0.31	0.16	—
Modulus of rupture, p.s.i.	14,400	14,600	13,000	13,500	9,100	1,470

[a] Fractions obtained by precipitation from acetone solution by adding isopropyl alcohol. Fractions ranged in vinyl chloride content from 83.1 to 86.4%. Molecular weights were determined by viscosity in dipropyl ketone at 20°C., using $K_m = 3.4 \times 10^{-4}$ in the simple Staudinger equation.

copolymer of vinyl chloride and vinyl acetate containing approximately 91%, 3%, and 6% respectively of vinyl chloride, vinyl acetate, and vinyl alcohol.

Other Vinyl Chloride–Unsaturated Ester Copolymers. Vinyl esters other than vinyl acetate have not attained commercial significance for use with vinyl chloride in interpolymer systems. Vinyl formate–vinyl chloride copolymers were covered in patents (17), but such products have not been marketed. Vinyl benzoate is now available, but no copolymers have yet been commercialized. Vinyl stearate and oleate esters have been interpolymerized with vinyl chloride by the Eastern Regional Laboratory, to give polymers with properties described as being internally plasticized; however, there are as yet no products offered for sale in commercial quantities.

Other unsaturated esters which have been interpolymerized with vinyl chloride include diethyl maleate (27) and diethyl fumarate (31). Since both have faster reaction rates than vinyl chloride, proportioning of the faster-reacting monomers has been proposed (13) to produce a more uniform copolymer. The maleate and fumarate copolymers with vinyl chloride have properties generally similar to the vinyl chloride–vinyl acetate copolymers with slightly elevated softening points.

Acrylic esters have been copolymerized with vinyl chloride by I. G. Farben to give a wide range of compositions and properties. Since the lower acrylate esters also enter the polymer chain faster than vinyl chloride, more uniform polymers have been obtained by batch-charging the vinyl chloride and proportioning the acrylate ester (16). Increasing the ratio of methyl acrylate in the vinyl chloride copolymer from 0 to 20% decreased the softening point from 78 to 63°C. (4). As would be expected, the higher acrylate esters enter the polymer chain more slowly and give copolymers with lower softening temperatures.

Copolymers with 90/10 ratio of vinyl chloride–acrylate esters are reported (9) to have the following softening points: methyl acrylate, 73°C.; ethyl acrylate, 67°C.; butyl acrylate, 65°C.; octyl acrylate, 64°C. Because of the relatively high price of acrylate esters in the U.S., commercial emphasis has been largely on the lower-priced vinyl acetate. Both the acrylate and methacrylate esters have been copolymerized with vinyl chloride by Rohm & Haas (7), and Smith of B. F. Goodrich Co. has prepared copolymers of ethyl acrylate and vinyl chloride as stable latex systems (34).

Vinyl Chloride–Vinylidene Chloride. To decrease the softening temperature and increase the solubility of polyvinyl chloride, I. G. Farben developed a technique for chlorination of the polymer suspended in a chlorinated solvent. Such polymers were appreciably more soluble, but were too unstable for wide commercial usage. Alexander and Tucker (28) prepared polymers with equivalent solubility and chlorine

contents, but with appreciably increased stability, by copolymerizing vinyl chloride and vinylidene chloride in suspension systems catalyzed by benzoyl peroxide. A series of such copolymers with varying solubilities was found to have somewhat better stability, tensile, and elongation properties than the after-chlorinated polyvinyl chlorides with corresponding chlorine contents.

Scott and Seymour (30) obtained a granular product when the following composition was reacted at 32°C. for about 16 hours: 35 parts vinyl chloride, 15 parts vinylidene chloride, 60 parts water, 1.5 parts Aquarex D, 0.11 part citric acid, 0.4 part sodium perborate, 1.6 parts carbon tetrachloride, and 0.72 part disodium hydrogen phosphate.

Vinyl chloride-vinylidene chloride copolymers ranging in composition from 95/5 to 85/15 are finding uses in calendering and extrusion compounds where lower processing temperatures are required. Higher ratios of the vinylidene chloride component up to 40% are used in solution resins. For copolymers of the saran type comprising 80–90% of vinylidene chloride see "Vinylidene chloride."

Applications of Vinyl Chloride Polymers and Copolymers

These polymers and copolymers can be divided into six types: (*1*) general-purpose resins, high-molecular-weight resins used in plasticized form for most applications; (*2*) dispersion resins, high-molecular-weight resins of small particle size suitable for dispersion in plasticizer, as plastisols and organosols; (*3*) water-dispersed resins, latexes; (*4*) solution-type resins, lower molecular-weight resins or copolymers which will dissolve in organic solvents; (*5*) nitrile rubber plasticized resins, polyblends; (*6*) rigid resins, copolymers or high-molecular-weight resins designed for unplasticized applications.

See such articles as *Cable coverings*; *Coated fabrics*; *Paper coatings* (*organic*). See also *Textile fibers* (*acrylic and vinyl*), Vol. **13,** p. 831.

General-Purpose Resins. These high-molecular-weight polymers are either straight polyvinyl chloride or they may contain a small amount of a copolymer such as vinyl acetate or vinylidene chloride. Within this group are electrical grade and powder mixing grade resins. The bulk of vinyl applications may be filled with these general purpose resins.

The basic resins are easily modified to meet a wide variety of requirements. Plasticizers play a most important role. They are high-boiling esters: phthalates, phosphates, adipates, sebacates, azelates, and polymeric-type esters. The amount used determines the degree of flexibility, and the type determines the physical and chemical properties. Stabilizers are used to prevent decomposition if the resin is subjected to excessive heat during processing or service life. They also help to prevent degradation by ultraviolet light. They are generally metallic compounds of lead, tin, barium, or cadmium. Small amounts of lubricants are processing aids. Fillers, such as clay or whiting, are used to reduce costs. Since the basic resins are transparent, color possibilities are unlimited. Both organic and inorganic color pigments are used. These ingredients are incorporated in the resin by mill, Banbury, or dry powder mixing.

Extrusion and injection molding, and calendering for sheeting, are commonly used fabricating methods.

The basic properties of polyvinyl chloride, its resistance to weathering, chemical

inertness, and electrical resistivity, and the ease of adapting its inherent properties to meet specific requirements, have been responsible for its widespread use. Not only its electrical properties, but also its oxidation resistance, nonflammability, and ease of fabrication have made it a leading material for wire and cable insulation. Tough cable jackets can be compounded to meet the exacting low-temperature requirements of military field communication wire as well as the underwater conditions encountered in the ocean. Other applications are garden hose, gaskets, and welting for shoes, upholstery, and automobiles.

Film and sheeting account for a substantial share of the vinyl resin produced. The attraction of an infinite variety of colors and designs, ease of cleaning, and water resistance have led to uses such as shower curtains, bedspreads, draperies, garment bags, table covers, place mats. Outdoor uses vary from wading pools to protective covers for outside storage. Polyvinyl chloride is adaptable to heat-sealing by high-frequency heating, and most items made from film such as rainwear and inflatable toys are fabricated by this method.

Commercial general-purpose resins[a]	Manufacturer
Geon 101 (E), 101-EP (E,P), 103-EP (E,P), 202	B. F. Goodrich Chemical Co.
Vinylite VYNW (E), QYNA (E), QYSQ (E,P)	Bakelite Div. of Carbide & Carbon Corp.
Opalon 300 (E,P)	Monsanto Chemical Co.
Marvinol VR-10, VR-22 (P,E), VR-20, VR-21, VR-30 (P)	Naugatuck Chemical Co.
Exon 500 (E,P), 905 (P), 915 (P), 925 (P)	Firestone Tire & Rubber Co.
Dow 111-1 (P), 111-4 (P,E), 100-4 (P), 100-5 (P)	Dow Chemical Co.
Diamond PVC-50 (powder) (P)	Diamond Alkali Co.
Goodyear EDB-90V (E,P)	Goodyear Tire & Rubber Co.

[a] E = electrical grade. P = powder mixing grade.

Dispersion Resins—Plastisols and Organosols. Plastisols are dispersions of vinyl resins in plasticizer. If the liquid phase contains volatile, nonaqueous materials, the system is called an organosol. These dispersion systems depend on the fact that the resin is relatively insoluble in plasticizer at room temperature, yet soluble at elevated temperatures. To obtain maximum physical properties it is necessary to fuse the compound at a temperature of 300–375 °F.

Organosol resins have a particle size ranging from 0.2 to 2.0 μ and are usually supplied as agglomerates of individual particles. Ball and pebble mills are effective in reducing these agglomerates as well as providing a closed system to contain the volatile liquids. The composition of the liquid phase (dispersant/diluent ratio) is critical, and determines the viscosity and stability of the system. The dispersant (plasticizer and volatile solvents such as ketones or esters) tends to wet and swell the resin, while the diluent (aromatic or aliphatic hydrocarbons) controls the swelling and reduces viscosity and cost. All the usual compounding ingredients (fillers, stabilizers, color pigments) may be added with the resin if desired.

Plastisols are mixed in shearing-type rather than high-speed mixers, and at room temperature (preferably below 90 °F.). Since plasticizer is the sole dispersing medium, its choice determines the flow properties which are vital to success in any application. Stabilizers, fillers, and color pigments are usually predispersed in plasticizer before being added to the plastisol. Because of the relatively high viscosity of plastisols, air entrapped during mixing fails to escape and must be removed for most applications by subjecting the plastisol to a vacuum.

The bulk of vinyl dispersions are used in the coating field on fabric or paper. Coated fabrics comprise the largest portion of the coating field and find their principal use in upholstery. Other applications are in rainwear, table covers, tarpaulins, wall coverings, flooring, protective clothing, rug backing, and conveyor belting. Vinyl coatings on paper are used for table and shelf covers, novelties, furniture decorations, floor and wall coverings. Coatings on synthetic-rubber-saturated papers are used as shoe innersoles, automobile door linings, and luggage.

Dip-coating is also an effective method of application. Electroplating racks, wire goods such as dish drainers, fabric gloves, automotive seat springs, lamp sockets, and strippable coatings on metal are typical of the products made. With plastisol systems, coatings up to 0.060 in. may be applied in a single dip. In multiple dipping, each coat is usually gelled separately, and final fusion is carried out after all coats have been applied. Heavier coatings may be applied from plastisols using a hot dipping process.

Gelling agents such as a metallic soap or a high oil absorption filler are used to prepare *plastigels*, which are plastisols having extremely high viscosities and yield values. Putty-like pastes may be prepared in this way and are applied by grease gun or trowel as sealants. Infrared lamps are used for fusion.

Slush and rotational molding are used to make hollow flexible articles, particularly toys, dolls, doll parts, and balls. A hollow mold is preheated and filled with plastisol. The portion adjacent to the wall is gelled by the heat of the mold. The remaining fluid plastisol is drained out and the mold sent through a fusion oven. After cooling in a water chamber, the article is removed by an air stream, and the operation repeated.

Vinyl sponge and foam are made from plastisols. Flotation equipment and insulation are made from closed cell sponge which is produced with chemical blowing agents in closed molds under pressure. Open cell sponge may be made with a chemical blowing agent without pressure or by dissolving an inert gas in a plastisol under relatively high pressure. Foamed vinyl is used in many applications such as mattresses, seating, automobile arm rests, and gasketing.

Commercial dispersion resins	Manufacturer
Geon 121, 126	B. F. Goodrich Chemical Co.
Vinylite QYNV	Bakelite Div. of Carbide & Carbon Corp.
Opalon 410	Monsanto Chemical Co.
Marvinol VR-10	Naugatuck Chemical Co.
Exon 654	Firestone Tire & Rubber Co.
Pliovic AO	Goodyear Tire & Rubber Co.
Dow X2702	Dow Chemical Co.

Water-Dispersed Resins—Latexes. Vinyl latexes are water dispersions of polyvinyl chloride or copolymers of vinyl chloride. The individual particles are negatively charged and are about 0.2 μ in diameter. These colloidal dispersions contain about 50% solids and are offered as resin or preplasticized resin latexes, having a pH of 7–9. Latexes may be compounded with plasticizers, fillers, and pigments like other vinyl resins, although the ingredients must be added as alkaline water solutions, emulsions, or dispersions.

After the latex is applied to the paper or fabric, water must be evaporated at about 75–80°F. for some latexes, but others must be fused at elevated temperatures of 250–

300°F. Embossing, printing, and smoothing are typical of the additional processing steps which may be used.

Vinyl latexes are used as "bridge" coats or tie coats on loosely woven fabric which is subsequently to be coated with an organosol or plastisol. Adhesion is improved and excessive penetration prevented. These coatings are also used for upholstery, luggage, shade cloth, and table covers. The strength, abrasion resistance, and good aging properties of vinyl latexes make them suitable as felt coatings for automobile trunk linings, and as binders and back-sizes for carpets.

Decorative coatings on paper, such as shelf and wall paper, take advantage of the ease of coloring, clarity, gloss, and light stability of many of these resins. Among other applications are heat-sealable coatings, prime coats on paper-surfaced wallboard, disposable paper sanitary products, rubber release coatings on paper tapes, and interior and exterior coatings on fiber drums.

In impregnation and saturation operations, vinyl latexes are used as binders and flameproofing agents for nonwoven fabrics, as for protective clothing and hospital sheeting. Drinking cups, shoe linings, and bookcovers may be made from paper saturated with these latexes.

Another important field of application is that of pigment binding for such products as printing inks, leather finishes, and emulsion paints.

Commercial vinyl latexes	Manufacturer
Resin latexes	
Geon 151, 251, 351, 352, 652	B. F. Goodrich Chemical Co.
Pliovic 300	Goodyear Tire & Rubber Co.
Exon 700XR59	Firestone Tire & Rubber Co.
Polyco 446	American Resinous Chemicals Co.
Preplasticized resin latexes	
Geon 576, 577, 552	B. F. Goodrich Chemical Co.
Dow 744-B	Dow Chemical Co.

Solution Resins. Coatings made from these resins are used to line beverage containers, closures, food-packaging paper, and beverage dispensers, and on kitchen furniture, medicine cabinets, refrigerator parts, and the like. Their toughness and flexibility enable them to withstand drawing, stamping, and forming operations after being coated on flat metal sheets.

Strippable coatings are applied with these resins by dipping or spraying. The films deposited provide excellent protection during storage and shipment. Large, irregular shapes may be covered effectively with a "cocoon-like" coating. The equipment is first covered with a web of pressure-sensitive tape. A special vinyl webbing solution is then sprayed over the tape framework.

Commercial solution resins	Manufacturer
Vinylite VMCH, VYHH, VYLF, VAGH, VYDR, VYCM, VYCC, VYNS	Bakelite Div. of Carbide & Carbon Corp.
Geon 200X20, 400X74L, 400X110, 400X80	B. F. Goodrich Chemical Co.
Exon 400XR70, 400XR71, 450, 470	Firestone Tire & Rubber Co.

Nitrile Rubber Plasticized Vinyls. Liquid plasticizers normally used with vinyl resins have some drawbacks such as volatility, extractability, and tendency to migrate to other materials. Butadiene-acrylonitrile polymers, being effective though less

efficient plasticizers, overcome these shortcomings in many cases. The nitrile rubber and the vinyl resin are preblended, in the colloidal state. The product, called a *polyblend*, is offered in sheet form. It is usually used as a thermoplastic material, although it can also be vulcanized.

Standard vinyl stabilizers, lubricants, and pigments are added on a cold or hot mill. Polyblends can be extruded, molded, or calendered. If better physical and extraction properties are desired, polyblends can be vulcanized with the usual rubber curing agents. These may be added on a cold mill.

Polyblends are used in such applications as film for food packaging, shoe welt, and electric cords which come in contact with styrene products such as clock cases. The most important electrical application is in jackets for coaxial cables. Calendered products are used in the textile and flooring fields. Vulcanized polyblend is used in printing roll covers, gaskets, and basketball covers.

Polyblends are also available in latex form. As such they are used as a grease-proof coating on paper, a fiber binder, and as a coating on felt for trunk linings.

Commercial resins	Manufacturer
Geon Polyblend 503-11	B. F. Goodrich Chemical Co.
Geon Polyblend Latex 552	B. F. Goodrich Chemical Co.

Rigid Resins. These resins are supplied both as powders and as finished compounds in granular form. Those processed without the use of plasticizer are the most important and may be divided into two groups: (*1*) high-molecular-weight resins used primarily for corrosion resistance, and (*2*) lower-molecular-weight resins used for phonograph records. It is necessary to add stabilizer, lubricant, and pigment for processing purposes. Both types may be extruded, calendered, or molded, using somewhat different techniques.

Rigid vinyls are designed to take maximum advantage of the chemical inertness of polyvinyl chloride. Any modification in the form of copolymer or processing aids tends to detract from the inherent chemical resistance of the polymer, so that most corrosion-resistant applications make use of unplasticized high-molecular-weight polyvinyl chloride.

Pipe made of polyvinyl chloride is used to carry salt water and sour crude oil. Although paraffin sticks and builds up on the inner walls of metal pipe, it does not do so in polyvinyl chloride pipe. Polyvinyl chloride is also used in chemical plants as pipe, fittings, valves, ducts, hoods, and filter frames.

Parts may be joined by the hot gas welding method, friction welding, or by cementing. They may be sawed, machined, etc., on standard metal or woodworking tools.

In addition to standard grades of high-molecular-weight resins used in the unplasticized state, a high impact grade is offered. Although the chemical resistance and heat distortion of this type polymer are slightly poorer than the normal impact grade, the increase in impact strength (as measured on the Izod machine in foot-pounds per inch of notch) from 0.8 to 15.0 makes this resin preferable for most applications. Rigid sheets are used in tank linings, or may be vacuum-formed into a variety of articles such as advertising and highway signs, aircraft window frames, luggage, printing plates, chemical containers, refrigerator parts, and housings of all types.

In addition to phonograph records, the lower-molecular-weight copolymers are

used in vinyl-asbestos floor tiling, although plasticizer is used with it as part of the binder.

Commercial rigid resins	Manufacturer
High-molecular-weight	
Geon 103-EP, 404-HI (high impact)	B. F. Goodrich Chemical Co.
Vinylite QYNA	Bakelite Div. of Carbide & Carbon Corp.
Exon 402-A	Firestone Tire & Rubber Co.
Low-molecular-weight	
Geon 400X78, 205	B. F. Goodrich Chemical Co.
Vinylite VYHH	Bakelite Div. of Carbide & Carbon Corp.
Exon 468	Firestone Tire & Rubber Co.

Bibliography for Vinyl Chloride

(1) DeBell, J. M., Goggin, W. C., and Gloor, W. E., *German Plastics Practice*, DeBell and Richardson, Springfield, Mass., 1947.
(2) Douglas, S. D., and Stoops, W. N., *Ind. Eng. Chem.*, **28**, 1154 (1936).
(3) Fieser, L. F., and Fieser, M. A. D., *Organic Chemistry*, Heath, N.Y., 1944.
(4) Fikentscher, H., and Franke, W., Office Tech. Services Rept., *P.B.* 40,871.
(5) Ostromislensky, I., *Chem. Zentr.*, **1912, I**, 1980, 1983.
(6) Regnault, V., *Ann.*, **15**, 63 (1835); *Ann. chim. et phys.*, [*2*] 59 (1835).
(7) Riddle, E. H., Rohm & Haas, Private communication.
(8) Roberts, D. E., *J. Research Natl. Bur. Standards*, **44**, 221 (March 1950).
(9) Schildknecht, C. E., *Vinyl and Related Polymers*, Wiley, N.Y., 1952, p. 406.
(10) *Vinyl Chloride Monomer*, Technical Bulletin, The Dow Chemical Co., Feb. 1954.
(11) Vinyl Chloride Data Sheet, Manufacturing Chemists Association, Feb. 1954.
(12) Brit. Pat. 569,291 (May 30, 1954), J. J. P. Staudinger and C. A. Brighton (to Distillers).
(13) Brit. Pat. 581,995 (Nov. 13, 1946), J. J. P. Staudinger and C. A. Brighton (to Distillers).
(14) Fr. Pat. 951,620 (April 18, 1949), C. H. Alexander and F. K. Schoenfeld (to B. F. Goodrich).
(15) Ger. Pat. 278,249 (Oct. 2, 1917), F. Klatte and A. Rollett (to Chem. Fabrik Griesheim-Elektron).
(16) Ger. Pat. 629,220 (March 5, 1938), H. Fikentscher and J. Hengstenberg (to I. G. Farbenind.).
(17) Ger. Pat. 677,157 (June 20, 1939), H. Stark (to I. G. Farbenind.).
(18) U.S. Pat. 1,241,738 (Oct. 2, 1917), F. Klatte and A. Rollett (to Chem. Fabrik Griesheim-Elektron).
(19) U.S. Pat. 1,425,130 (Aug. 8, 1922), H. Plausen.
(20) U.S. Pat. 1,775,882 (Sept. 16, 1930), C. O. Young and S. D. Douglas (to Carbide & Carbon).
(21) U.S. Pat. 1,929,453 (Aug. 8, 1939), W. L. Semon (to B. F. Goodrich).
(22) U.S. Pat. 1,938,870 (Sept. 16, 1930), L. C. Shriver (to Carbide & Carbon).
(23) U.S. Pat. 1,935,577 (Nov. 14, 1933), E. W. Reid (to Carbide & Carbon).
(24) U.S. Pat. 2,064,565 (Dec. 15, 1937), E. W. Reid (to Carbide & Carbon).
(25) U.S. Pat. 2,075,429 (March 30, 1937), S. D. Douglas (to Carbide & Carbon).
(26) U.S. Pat. 2,168,808 (Aug. 8, 1939), F. K. Schoenfeld (to B. F. Goodrich).
(27) U.S. Pat. 2,187,879 (Jan. 23, 1940), H. Hopff, G. Steinbrunn, and H. Freudenberger (to I. G. Farbenind.).
(28) U.S. Pat. 2,245,742 (June 17, 1941), C. H. Alexander and H. Tucker (to B. F. Goodrich).
(29) U. S.Pats. 2,345,659-60 (April 4, 1944), A. W. Downes (to Carbide & Carbon).
(30) U.S. Pat. 2,348,154 (May 2, 1944), W. Scott and R. B. Seymour (to Goodyear).
(31) U.S. Pat. 2,395,581 (Feb. 26, 1946), H. J. Richter (to Du Pont).
(32) U.S. Pat. 2,458,636 (Jan. 11, 1949), L. Plambeck (to Du Pont).
(33) U.S. Pat. 2,474,206 (June 28, 1949), W. L. J. de Nie (to Shell Development Co.).
(34) U.S. Pat. 2,510,426 (June 6, 1950), G. W. Smith (to B. F. Goodrich).
(35) U.S. Pat. 2,520,959 (Sept. 5, 1950), J. R. Powers (to B. F. Goodrich).
(36) U.S. Pat. 2,569,923 (Oct. 2, 1951), H. A. Cheney (to Shell Development Co.).

CLAUDE H. ALEXANDER AND GERARD F. COHAN

VINYLIDENE CHLORIDE

The existence of vinylidene chloride was known for nearly a hundred years before extensive research was carried out on the polymers of this compound. The French chemist Regnault reported in 1838 the formation of a white "noncrystalline" precipitate from a liquid boiling between 35 and 40°C. The liquid was apparently an impure 1,1-dichloroethylene prepared from trichloroethane by reaction with alcoholic potassium hydroxide. Regnault regarded this precipitate as an isomeric modification of the liquid. Further mention of this substance is occasionally found in the literature (6,8,9), but it was not until 1932, when The Dow Chemical Company began a thorough investigation of vinylidene chloride polymers, that promise of commercial use became evident. This work led to the introduction in 1939 of a family of thermoplastics based on vinylidene chloride and now known generically as "saran." (In many foreign countries, Saran is a registered trademark of The Dow Chemical Company.)

The term saran refers to polymers that contain 50 or more per cent vinylidene chloride. The vinylidene chloride homopolymer, although having better chemical resistance, higher heat distortion temperatures, and lower water-vapor and gas transmission rates than the copolymers, is of little commercial significance due to the limited heat stability encountered at the high temperatures required for plastic working of the material. Copolymerization, for example, with vinyl chloride or acrylonitrile, greatly increases the softening range, making it suitable for conventional plastic extrusion or injection molding fabricating techniques at temperatures well below its decomposition temperature. Although the excellent properties of the homopolymer must be sacrificed to some degree by copolymerization in order to obtain the necessary processing characteristics, these copolymers are, nevertheless, noted for their excellent chemical resistance and vapor barrier characteristics in combination with other desirable properties. Saran is produced in shapes by the usual extrusion and injection molding techniques. It can be fabricated into high-strength monofilaments or thin, highly impermeable films by a process of crystalline orientation, and is also used in numerous applications in coatings.

Vinylidene Chloride Monomer

Vinylidene chloride monomer (1,1-dichloroethylene), formula weight 96.95, is a colorless liquid which has a sweet pleasant odor, although it develops a sharp disagreeable odor after contact with air. It polymerizes slowly in the absence of oxygen. Table I lists its important properties.

Preparation. The monomer can be conveniently prepared in the laboratory by the reaction of 1,1,2-trichloroethane (see Vol. **3**, p. 765) with aqueous alkali:

$$2\ CH_2ClCHCl_2 + Ca(OH)_2 \xrightarrow{90°C.} 2\ CH_2{=}CCl_2 + CaCl_2 + 2\ H_2O$$

Although this general reaction was used by many early investigators, it became the subject of several later patents (13,14). Vinylidene chloride monomer can also be obtained by the catalytic cracking of trichloroethane as well as by other methods. Monomer is commercially prepared by the dehydrochlorination of trichloroethane made by the chlorination of ethane.

Storage. Vinylidene chloride monomer handling requires certain safety precautions. The monomer is flammable, burning strongly but not violently. The vapors

TABLE I. Properties of Vinylidene Chloride Monomer.

Property	Value
B.p., °C.	31.7
M.p., °C.	−122.53
d_4^{20}	1.2181
dd/dt, approx.	0.0016
n_D^{20}	1.4271
Vapor pressure, mm.	
At 0°C.	215.9
At 25°C.	599.0
Viscosity, centipoises	
At 0°C.	0.422
At 20°C.	0.358
At 50°C.	0.292
Sp.heat, cal./(g.)(°C.)	0.27
Heat of polymerization, kg.-cal./mole	14.4
Heat of fusion, cal./g.	1.7
Heat of vaporization, cal./g.	66.8
Flash point, Cleveland open cup, °C.	−10
Explosive limit in air at 25°C., %	7–16
Dielectric constant at 1,000 cycles/sec.	4.5–5.0

are hazardous to breathe. For regular daily operations, vapor concentrations should not reach more than 100 p.p.m. Prolonged or repeated contact of the skin with monomer should be avoided to prevent skin irritation.

The storage of uninhibited monomer is conducive to peroxide formation which presents an explosion hazard. When vinylidene chloride is stored without a polymerization inhibitor at temperatures below about 25°C. in the presence of air or oxygen, the oxygen dissolves and reacts rapidly to form a peroxide compound of undetermined structure. This peroxide may be a polymerization catalyst, and its formation is often accompanied by the precipitation of a flocculent vinylidene chloride polymer. This peroxide compound is violently explosive, and since it is adsorbed on the precipitated polymer, any separation of this polymer by filtration, evaporation, or drying will result in an explosive composition. Any such composition containing more than about 15% of the peroxide will, if dry, detonate from a slight mechanical shock or from heat. Compositions that contain reaction products of vinylidene chloride and ozone are particularly dangerous. It may be noted that polyvinylidene chloride free of peroxides is not explosive.

The end products of the slow decomposition of vinylidene chloride peroxides are formaldehyde, phosgene, and hydrochloric acid. Therefore, if the monomer has a sharp acid odor, it has been exposed to oxygen and may contain peroxides. The formation of polymer when no catalysts have been added is another indication of possible oxygen contamination. The presence of peroxides may be confirmed by the liberation of iodine from a slightly acidified dilute potassium iodide solution according to standard analytical procedures. These peroxides may be decomposed and removed from vinylidene chloride by several washes with fresh 5% $NaHSO_3$ solution or with 10% NaOH at 25°C.

Storage of vinylidene chloride in the absence of air or oxygen is the positive method for preventing the formation of peroxides. However, many inhibitors for the polymerization of vinylidene chloride have been described in patents (16–18), and

there is evidence that phenol-type polymerization inhibitors, when added to vinylidene chloride, will delay or prevent the formation of peroxide compounds. It is this class of inhibitors which is recommended.

In research and plant work, monomer residues may be found in bottles, distillation flasks, condensers, filters, pipe lines, drums, and tanks. These residues should be handled with great care and may be rendered inactive by contacting with water at room temperature, although upon drying up, the peroxides will again become dangerous. Large-scale equipment that is used intermittently should be filled with water during shut-down periods.

Homopolymerization

Pure liquid vinylidene chloride, free of oxygen, polymerizes very slowly. As ordinarily prepared, however, vinylidene chloride polymerizes readily at temperatures above 0 °C. to form a polymer which is insoluble in the monomer and precipitates as a white powder (19). The presence of dissolved oxygen, which reacts to form peroxides

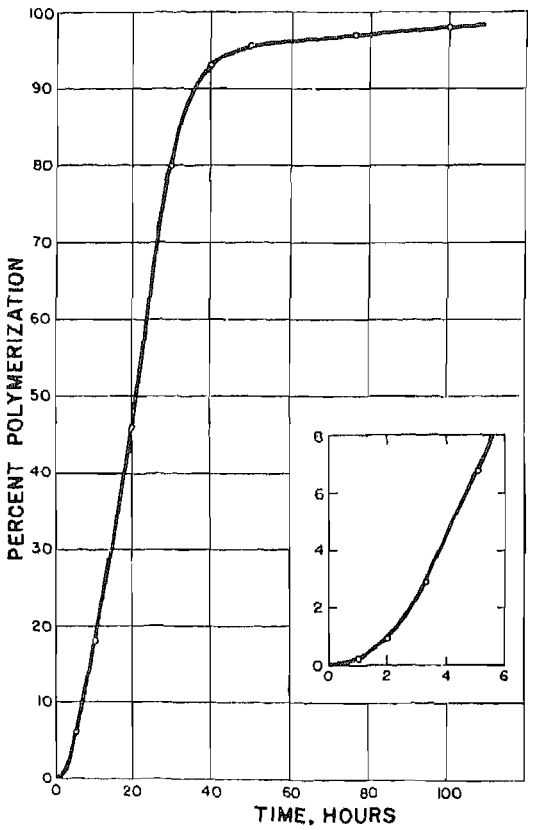


Fig. 1. Polymerization of vinylidene chloride (catalyst 0.50% benzoyl peroxide; temp. 45°C.; dark) (7).

and acid chlorides, catalyzes the polymerization. Although vinylidene chloride is not strictly a vinyl compound, much of the technique of vinyl chloride polymerizations is applicable. The preferred polymerization catalysts for vinylidene chloride

are of the free radical type, such as peroxides, potassium peroxysulfate, and 2,2′-azodiisobutyronitrile.

Benzoyl peroxide in concentrations of 0.05–2.0% has been used frequently in laboratory work, and a typical polymerization curve is shown in Figure 1. The straight-line nature of these curves is characteristic. The benzoyl peroxide–catalyzed polymerizations have little, if any, induction period above 30°C., but usually show a lower polymerization rate for the first few per cent conversion. This behavior is illustrated by the enlarged portion of the curve inset in Figure 1.

The use of other catalysts or combinations of catalysts causes wide variation in polymerization rates but, in general, does not change the shape of the curves. Thermal polymerization of vinylidene chloride without added catalyst usually does not occur at a rate sufficiently high to be useful, but photopolymerization has been successful both with and without auxiliary chemical catalysis. Light of wave length less than 4500 A. causes polymerization at temperatures as low as −35°C.

Since the polymer is not soluble in the monomer, a solid phase appears during the polymerization of vinylidene chloride. In mass or bulk polymerizations, where only monomer and catalyst are present, the polymer appears as a flocculent precipitate until between 10 and 20% conversion, when the slurry becomes solid. Above 20%, no liquid is visible, and the porous solid becomes harder with increasing polymerization. With proper choice of conditions, the reaction reaches 100% conversion to polymer and results in a heat evolution of about 14,400 calories per mole of monomer. To control the rate of polymerization and the physical characteristics of the product, it is often desirable to disperse the monomer in a solvent or an immiscible liquid and conduct the polymerization in solution, emulsion, or other dispersed system (23). The products of different polymerization methods differ only in minor details.

Polyvinylidene chloride, $(—CH_2CCl_2—)_n$, molecular weight 10,000–100,000, is a white, porous and nonflammable powder with a softening range of 185–200°C. and a decomposition temperature of about 225°C. When fused and cooled, the polymer is colorless and nearly transparent. In either form, polyvinylidene chloride possesses two outstanding characteristics; crystallinity, as determined by x-ray diagrams, and insolubility. (It is insoluble in practically all organic solvents at temperatures below 100°C., and is unaffected by common reagents at temperatures below 100°C.)

The distinctive properties of polyvinylidene chloride are given in Table II. The utilization of the polymer as a plastic material in the ordinary sense is difficult because of its high softening range, its tendency to evolve hydrogen chloride at the temperatures required for plastic working, and its incompatibility with the usual plasticizers. These properties, not necessarily disadvantages, are characteristic of the molecule; but despite them, polyvinylidene chloride can be worked by special methods to produce a unique plastic material. For general use, the properties of the polymer are best modified by copolymerization.

TABLE II. Properties of Polyvinylidene Chloride.

Property	Value
Softening temp., °C.	185–200
Decomposition temp., °C.	210–225
Density, at 30°C., g./cu.cm.	1.875
n_D^{30}	1.63

Source: Ref. (7).

Copolymerization

Vinylidene chloride forms copolymers with many substituted ethylenes (particularly the common vinyl compounds), with dienes and their derivatives, and with a number of other unsaturated compounds. Specific examples are described in many

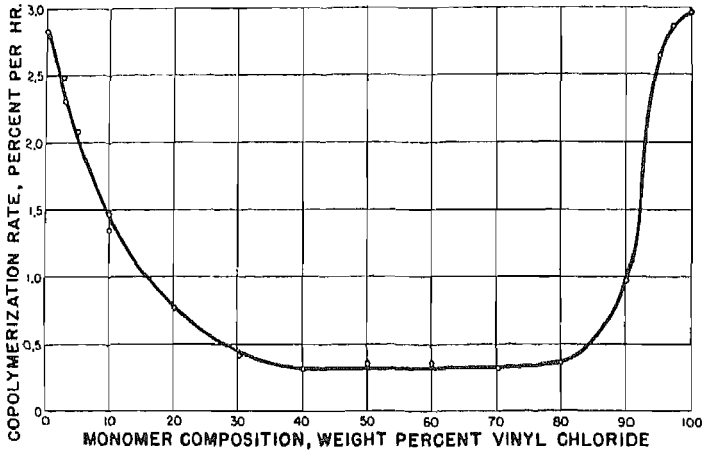


Fig. 2. Copolymerization rate of vinylidene chloride and vinyl chloride as a function of monomer composition (catalyst 0.50% benzoyl peroxide; temp. 45°C.; dark) (7).

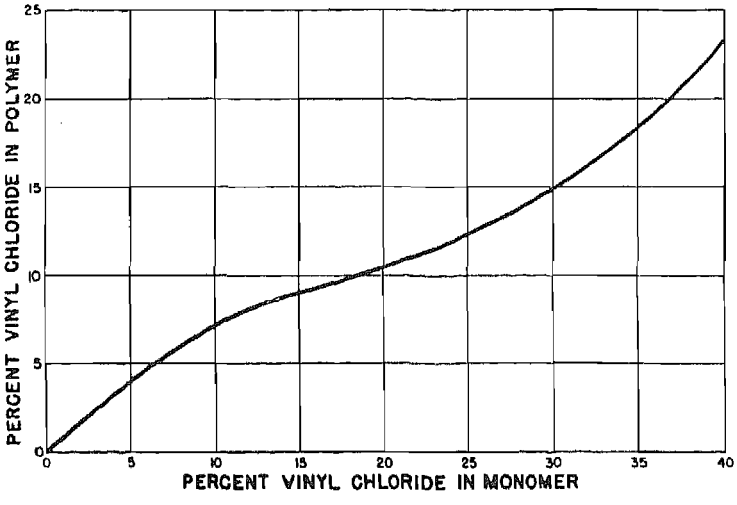


Fig. 3. Copolymerization of vinylidene chloride and vinyl chloride (catalyst 0.50% benzoyl peroxide; temp. 45°C.; dark; approx. 50% polymerization) (7).

patents. The most important copolymers of vinylidene chloride are those with vinyl chloride (10,21,34,36) and acrylonitrile (35). Other compounds that are known to copolymerize with vinylidene chloride are vinyl acetate (21), styrene (22), esters of acrylic and methacrylic acid (11,26), butadiene and its derivatives (12,15,31), various unsaturated esters (24,27), unsaturated ethers (25), and halogen-substituted propenes (28).

In general, when vinylidene chloride is copolymerized, each mixture of monomers has a different polymerization rate and produces a polymer of different composition. In the case of vinyl chloride, the product contains a larger proportion of vinylidene chloride than the original monomer mixture, and the rate of polymerization is slower than for either monomer alone. A typical case is illustrated by Figure 2. Although vinylidene chloride and vinyl chloride have nearly identical polymerization rates with 0.5% benzoyl peroxide at 45°C., mixtures of the two monomers may have but one-tenth the polymerization rate of either component.

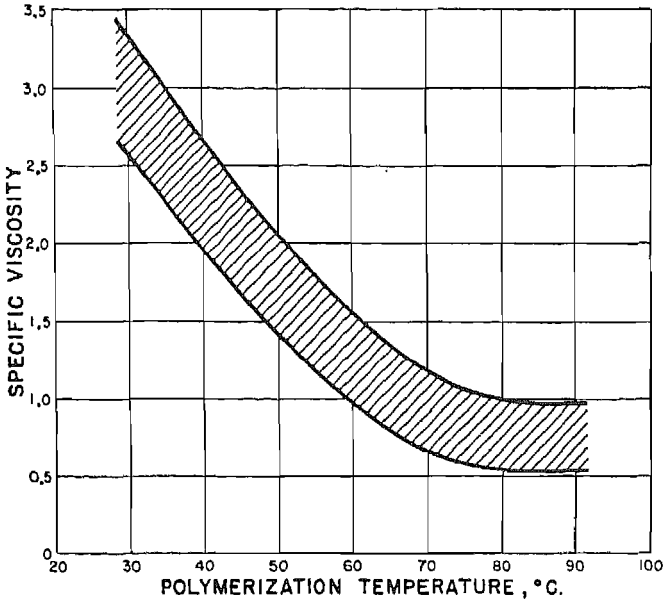


Fig. 4. Specific viscosity of vinylidene chloride–vinyl acetate copolymers as a function of polymerization temperature (monomer composition 85% vinylidene chloride, 15% vinyl acetate; catalyst 0.50% benzoyl peroxide; dark; solution, 2% in o-dichlorobenzene at 120°C.) (7).

Except in rare cases, the products are true copolymers and contain little or none of the individual polymers. Figure 3 shows the average polymer compositions produced from a number of monomer mixtures. Since the polymer contains more vinylidene chloride than the monomer the vinyl chloride concentration in the monomer increases as polymerization progresses. Consequently the product of such a polymerization usually contains a wide distribution of copolymer compositions in addition to the distribution of chain lengths.

The rate of peroxide-catalyzed copolymerization is increased by increasing the concentration of catalyst or by raising the temperature. Normally a balance between the two is arrived at in order to obtain the desired molecular weight. Increased temperature is preferable to higher catalyst concentration as a means of increasing the polymerization rate. The relation of viscosity (that is, chain length) to polymerization temperature for these copolymers is shown in Figure 4. The rapid change of specific viscosity with polymerization temperature is believed due to the chain transfer effects of vinylidene chloride.

The methods used for polymerizing vinylidene chloride are applicable with cer-

tain changes to the formation of its copolymers. However, the widely varying polymerization rates and the heterogeneous copolymers introduce important complications in the study and development of both process and products.

Vinylidene chloride copolymers may be analyzed by standard methods. Determination of the percentage chlorine is usually sufficient to give the average composition, although, as mentioned by Berger (1), the results obtained by this method may be in error by several per cent. Chain lengths are comparatively measured by the determination of solution viscosity, but owing to the extremely limited solubility of certain copolymers, it is often necessary to use only the best solvents at temperatures of 120°C. or above.

STRUCTURE

In contrast to most organic thermoplastics that exist only in the amorphous state, polyvinylidene chloride and its copolymers exist in a *crystalline* state. X-ray diffraction methods indicate a high degree of crystallinity for vinylidene chloride homopolymers but a proportionately lesser degree of crystallinity and an appreciable amount of

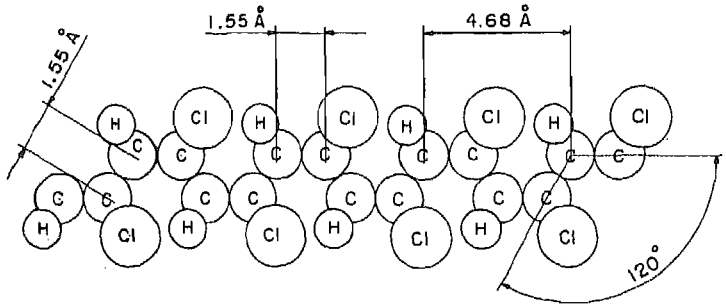


Fig. 5. Chain configuration of polyvinylidene chloride. (Scale of interatomic distances expanded with respect to that of atomic radii.) Each Cl and H atom is one of a pair, of which the other is not shown.

amorphous material for the copolymers. This is the normal crystalline "as-polymerized" state for these polymers.

If a polymer or copolymer of vinylidene chloride is melted at a temperature sufficiently high to destroy its crystallites, the material becomes *completely amorphous*. Amorphous polymer, upon being rapidly cooled to a low temperature, remains amorphous. Storage of the amorphous material at suitable temperatures permits control of the recrystallization rate. Amorphous polymer, upon standing at room temperature, or upon being heated without remelting, reverts to the normal state of high crystallinity. The crystallization induction time for amorphous vinylidene chloride homopolymer is so short that it is difficult to cool it from an elevated temperature rapidly enough to maintain the amorphous state. The induction time increases with increasing comonomer concentration.

A third modification of these polymers and copolymers is the *oriented crystalline* state, produced by severe mechanical working, as by stretching, of either completely amorphous or partly crystalline polymer. Orientation lines up the crystallites in the direction of stretch and produces a tough, strong, flexible material.

Accurate measurement and analysis of x-ray diffraction patterns, together with the above considerations, lead to a concept of the structure of polyvinylidene chloride

which is adequate to explain the observed physical phenomena. A single chain of polyvinylidene chloride is believed to have the structure of Figure 5. Monomer units are joined head to tail, with a serpentine configuration of carbon atoms. With a carbon valence bond angle of approximately 120° and a carbon-carbon distance of 1.55 A., an identity period of 4.68 A. results. A slightly different structure is offered by Fuller (3) who suggested a zig-zag arrangement of carbon atoms with the chain shortened by partial rotation.

Solution viscosity and osmotic pressure measurements indicate a range of chain lengths of 100–1,000 monomer units. As with other high polymers, the chain length is an inverse function of the polymerization temperature and the catalyst concentration. Determination of the branching coefficient, n, by the method of Houwink (5) gives $n = 1$. This unusually low value and the marked tendency to crystallize are strong evidence that the chains are not branched. In the amorphous state they are randomly distributed and probably highly curled. Crystallization involves the movement of portions of such molecules into a macromolecular lattice which has no well defined boundaries.

The unit cell of polyvinylidene chloride is monoclinic and contains four —CH_2-CCl_2— units. Its dimensions have been determined accurately as follows: $a = 13.72 \pm 0.015$ A.; $b = 4.68 \pm 0.01$ A.; $c = 6.31 \pm 0.01$ A.; $\sin \beta = 0.8212 \pm 0.015$; volume of cell = 332.7 A^3.

The dimensions of the crystallite are believed to be about 20–30 A. parallel to the chain axes, and about 200–500 A. at right angles. In the crystalline portions the chains are essentially parallel, although the long-chain molecules undoubtedly traverse both crystalline and amorphous regions. The comparatively low proportion (20–40%) of crystalline regions in fused and recrystallized polymer, and the high ratio of length to diameter of the molecules, indicate that the amorphous regions are probably the continuous phase. Such a picture is not one of mesomorphic arrangement or a crystalline modification dispersed in an amorphous one, but rather of a continuous transition between crystalline and amorphous material. Both modifications share in determining the ultimate physical properties.

Copolymerization introduces units in the chain that tend to destroy its regularity and consequently its ability to crystallize, although the introduction of small amounts of other monomers merely results in minor discontinuities in the crystalline regions. The magnitude of the effect varies with the structure of the copolymerizing molecule. The vinylidene chloride copolymers become essentially noncrystalline when the monomer mixture contains more than 50% vinyl chloride, 20% ethyl acrylate, or 15% acrylonitrile. Other effects of copolymerization that are related to the decreased crystallinity are reduced softening temperature and increased solubility in organic solvents.

EFFECTS OF CRYSTALLINITY

The crystalline copolymers of vinylidene chloride (with the exception of the as-polymerized powders) are hard, tough materials resembling ordinary plastics in many respects. In the amorphous state these polymers are soft, rubbery, capable of being mechanically worked, and tend to crystallize on standing at room temperature. The oriented modification is strong, tough, and very flexible. It is these copolymers that possess the most advantageous combination of properties for commercial molding and extrusion.

Saran has a very narrow softening range which is characteristic of the crystalline polymers and copolymers of vinylidene chloride. A few degrees above the softening range these polymers have a sharp, reproducible crystalline melting point which can be observed by the change in light transmission of a sample heated between crossed polaroids. This temperature probably corresponds to the melting of the most stable crystalline regions. The process of melting is comparable to the solid-liquid transition

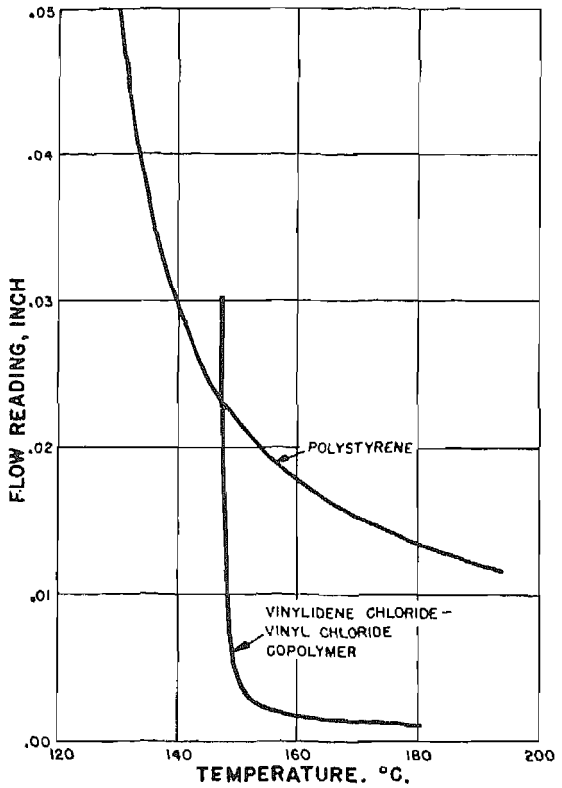


Fig. 6. Typical flow curves of a crystalline vinylidene chloride–vinyl chloride copolymer and polystyrene (flow reading is the equilibrium thickness attained by a film of plastic subjected to a constant load between parallel polished plates heated to the temperatures shown) (7).

of crystalline compounds of lower molecular weight. At higher temperatures the molten polymers may be quite fluid. The flow data in Figure 6 illustrate the sharp softening point of a crystalline vinylidene chloride–vinyl chloride copolymer as compared with polystyrene.

When a normally crystalline copolymer is heated to a temperature sufficient to melt the crystalline portion and then cooled rapidly to a low temperature so that no recrystallization occurs, it remains amorphous and is said to have been supercooled (30). When so treated, the tendency to crystallize is a function of many variables. The most important of these are the copolymer composition, the time and temperature of storage, and the presence of addition agents such as plasticizers. Figure 7 shows the wide variation with temperature of the induction time that elapses before

recrystallization begins. This induction period, as measured between crossed polaroids, is a reproducible quantity for any copolymer composition and treatment. Due to the short induction period at the lowest portion of the curves, very rapid cooling of the amorphous material is necessary to prevent recrystallization from taking place. A storage temperature of under 20°C. would be necessary to maintain the material in an amorphous state for any extended period of time. The effect of certain plasticizers in reducing the crystallization induction period may be attributed to the increased mobility of the chains.

As recrystallization progresses, several marked changes occur in the physical and mechanical properties of the polymer. The most important of these are: (*1*) the gradual development of a typical crystalline x-ray diffraction pattern; (*2*) an increase

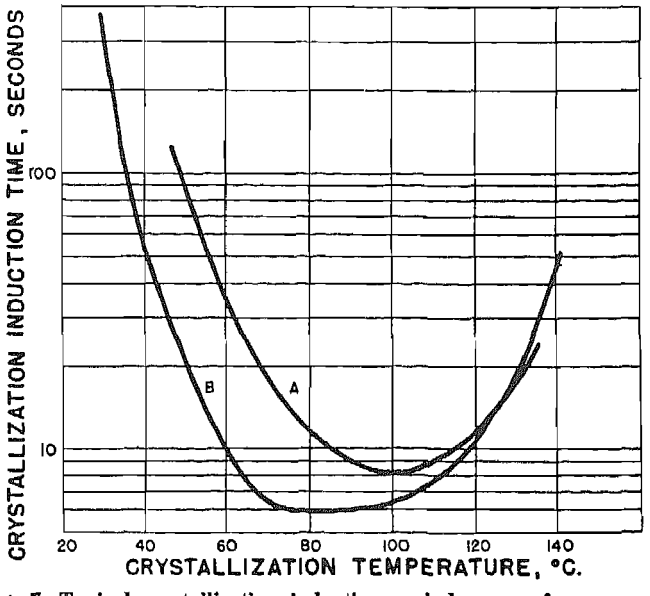


Fig. 7. Typical crystallization induction period curves for a normally crystalline vinylidene chloride–vinyl chloride copolymer. A, no plasticizer; B, 7% plasticizer; specimen thickness, 0.050 in. (7).

in hardness; (*3*) an increase in the force required to produce deformation; (*4*) an increase in density; (*5*) evolution of about 3.4 calories per gram of polymer as heat of crystallization; (*6*) a decrease in solubility; and (*7*) variations in electrical properties.

ORIENTATION PROPERTIES

Vinylidene chloride polymers and copolymers exhibit orientation when either the crystalline or amorphous modifications are mechanically worked. The degree of orientation produced may vary depending on the polymer composition and treatment. If a saran filament is stretched at a temperature somewhat above the crystalline melting point and quickly cooled, the strand will show some slight orientation. Crystalline saran filaments may also be stretched, with the application of comparatively high loads, and filaments so treated will exhibit orientation together with increased strength and flexibility. However, if a similar filament is supercooled and stretched before

recrystallization begins, a high degree of orientation results. This treatment may be used to produce fibers of exceptionally high strength and flexibility (33). The load elongation curve for a supercooled filament (see Fig. 8) shows that the force required for plastic deformation is nearly constant below 300% elongation, but after orientation has occurred, elastic elongation requires a relatively high load. Supercooled filaments may be stretched to an elongation of 350–400%, depending on pre-

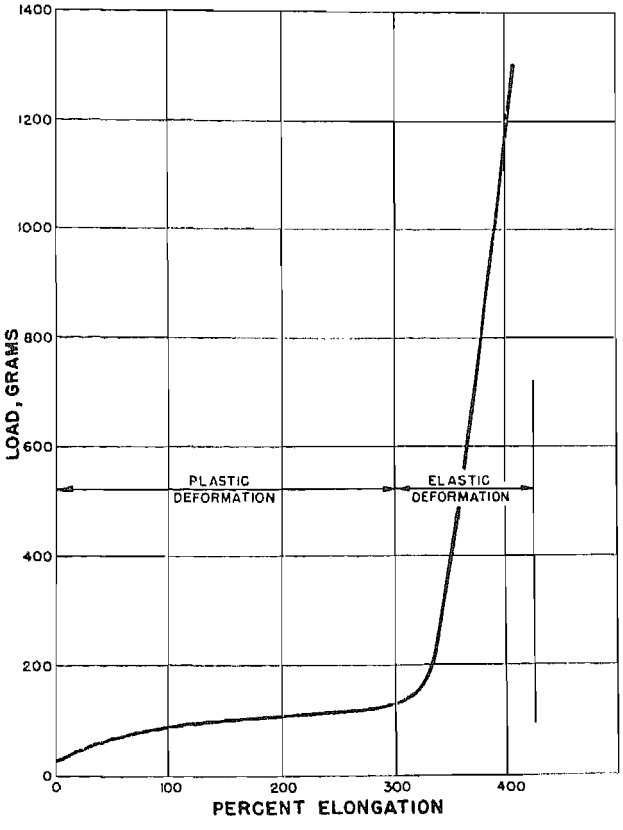


Fig. 8. Typical load-elongation curve for a supercooled filament of a normally crystalline vinylidene chloride–vinyl acetate copolymer, plasticized. (Temp. of test 20°C., Scott IP2 testing machine, final diameter of filament 0.011 in.) (7).

vious treatment. The greatest increase in tensile strength occurs with the last few per cent of stretch. Tensile strengths of 100,000 p.s.i. have been obtained with optimum stretching conditions, but with the sacrifice of other desirable properties.

Properties of Saran

The relative insolubility and unreactivity of polyvinylidene chloride were noted by a number of early workers. These characteristics are not greatly altered by increasing copolymerization until the copolymer contains less than about 85% of vinylidene chloride. Consequently, the commercially available sarans are resistant to the action of all but a few common reagents. At room temperature, tetrahydrofuran and tris(dimethylamido)phosphine oxide, $[(CH_3)_2N]_3PO$ (hexamethylphosphoramide (*C.A.*)),

TABLE III. Properties of Saran.

(Range in Properties Covers Several Types of Commercial Sarans.)

Property	Unoriented forms	Oriented forms
Sp. gr.	1.65–1.72	1.65–1.72
Fabricating information		
Compression molding		
Temp., °F.	250–350	—
Pressure, p.s.i.	500–5,000	—
Extrusion temp., °F.	300–400	300–400
Injection molding		
Temp., °F.	300–400	—
Pressure, p.s.i.	10,000–30,000	—
Mold shrinkage, in./in.	0.005–0.025	—
Mechanical		
Moduli of elasticity		
In tension, $\times 10^5$, p.s.i.	0.55–0.8	0.7–2.0
In compression, $\times 10^5$, p.s.i.	0.55–0.95	—
In flexure, $\times 10^5$, p.s.i.	0.55–0.95	—
Tensile strength,		
Upper yield, p.s.i.	2700–3700	—
Ultimate, p.s.i.	3000–5000	20,000–50,000
Compressive properties		
Yield strength, 0.2% offset, p.s.i.	2000–2700	—
Strength at 20% deformation, p.s.i.	4500–6100[a]	—
Flexural yield strength, p.s.i.	4300–6100[b]	—
Elongation in tension		
At yield, %	15–24	16–23
At ultimate, %	50–240	15–25
Hardness, Rockwell M	50–65	—
Impact strength, Izod notched, ft.-lb./in. of notch	0.3–1.0	—
Thermal		
Flammability (over 0.050 in.), in./min.	Self-extinguishing	
Flow temp., °F.	240–280	
Heat distortion, at 264 p.s.i., °F.	130–150	
Sp. heat, cal./(°C.)(g.)	0.32	
Thermal conductivity, cal./(sec.)(sq.cm.)(°C./cm.)	3.0×10^{-4}	
Thermal coefficient of expansion, (in./in.)/°C.	19×10^{-5}	
Optical		
n_D^{20}	1.60–1.63	—
Electrical		
Dielectric constant		
At 60 cycles/sec.	4.5–6.0	—
At 10^3 cycles/sec.	3.5–5.0	—
At 10^6 cycles/sec.	3.0–4.0	
Dielectric strength, short time, 1/8 in., volts/mil	350	—
Power factor		
At 60 cycles/sec.	0.030–0.045	—
At 10^3 cycles/sec.	0.060–0.075	—
At 10^6 cycles/sec.	0.045–0.065	—
Resistivity, volume, (ohm-cm.)	10^{14}–10^{15}	—
Chemical properties		
Water absorption, 24 hr., %	0.1	0.1
Exposure		
Color stability	Slight darkening	
Resistance to weathering	Slight darkening, otherwise excellent	

[a] No failure, continues to compress.
[b] No failure.

show good solvent action. Elevating the temperature makes it possible to obtain solutions with many other solvents such as cyclohexanone, cyclopentanone, dioxane, isophorone, and *o*-dichlorobenzene. At room temperatures, saran is substantially unaffected by most solvents of the following classes: aliphatic, aromatic and chlorinated hydrocarbons, alcohols, esters, and ketones. Inorganic acids and alkalies have little or no effect, with the exception of concentrated sulfuric acid, sodium hydroxide, and ammonium hydroxide which cause degradation and discoloration. The resistance to chemicals or solvents decreases with increase in temperature. The resistance of a saran to any chemical is in part a function of the crystallinity of the polymer. It is chemically more resistant in the crystallized form than in the amorphous state.

Saran's resistance to water is exceptional. A.S.T.M. tests show less than 0.1% water absorption in a 24-hr. period, and a water-vapor transmission rate of less than 0.2 g./100 sq.in./24 hr. at 100°F. for 1 mil film (4). (Dry on one side, 95% R.H. on the other side.)

The basic saran polymers are odorless, tasteless, and nontoxic. Their high refractive index enhances their many color possibilities. Their toughness and abrasion resistance are of a high order, and the retention of these properties upon aging insures excellent weaving qualities in filament form.

In view of the low compatibility of crystalline vinylidene chloride and copolymers with other materials, it is not surprising that only a limited number of plasticizers offer advantages (20,29,32). Plasticized and stabilized copolymer compositions of saran are available for molding and extrusion. Heat and light stabilizers, dyes, pigments, fillers, and lubricants have been developed specifically for many applications.

Table III lists the properties for a range of typical saran formulations. Table IV (see p. 753) contains general properties for a one-mil saran film.

Fabrication and Uses

Saran is adaptable to the conventional methods for the fabrication of plastics with minor modifications of equipment and techniques.

The **extrusion** of saran requires machine designs that will permit streamline plastic flow with minimum opportunity for plastic hold up to avoid the thermal decomposition of the saran in hot zones. Since the decomposition products of saran are carbon and hydrogen chloride, special metals of construction are required for the heated sections of the extruder to resist attack by hydrogen chloride. The metallic salts of iron, copper, tin, and zinc catalyze this decomposition. Recommended nickel alloy construction metals include Duranickel ("Z" nickel) for screws; Duranickel, Xaloy 306, Hastelloy D, or Stoody No. 6 for cylinder liners; "A" nickel nosepieces; and Duranickel dies. Dowmetal (magnesium) can be used for experimental dies but is too soft for production die use.

Plasticized and stabilized saran formulations are available in powder form for use in extrusion operations. The powder presents no bulk problem with the screw machine and eliminates a costly pelletizing step. Colored formulations are available as well as color concentrates that can be blended with a natural formulation by the fabricator.

In the extrusion process, saran is heated above its crystallite melting point where it becomes completely amorphous and very fluid. In this state it can be extruded with no plastic memory, making possible the retention of the desired shape and surface. The product, when first extruded and cooled in a water bath, is soft, weak, and

pliable. If it is allowed to remain at room temperature without further treatment, it will gradually harden while partially recrystallizing at a slow rate with a random crystal arrangement. By means of heat treatment, recrystallization can be produced at controlled rates, from a few seconds to several weeks. The rate of recrystallization is a function of temperature as shown in Figure 9.

The control of extrusion and heat-treatment conditions with saran permits a range of product properties to be obtained. (See Table III.) Such products have excellent fatigue life.

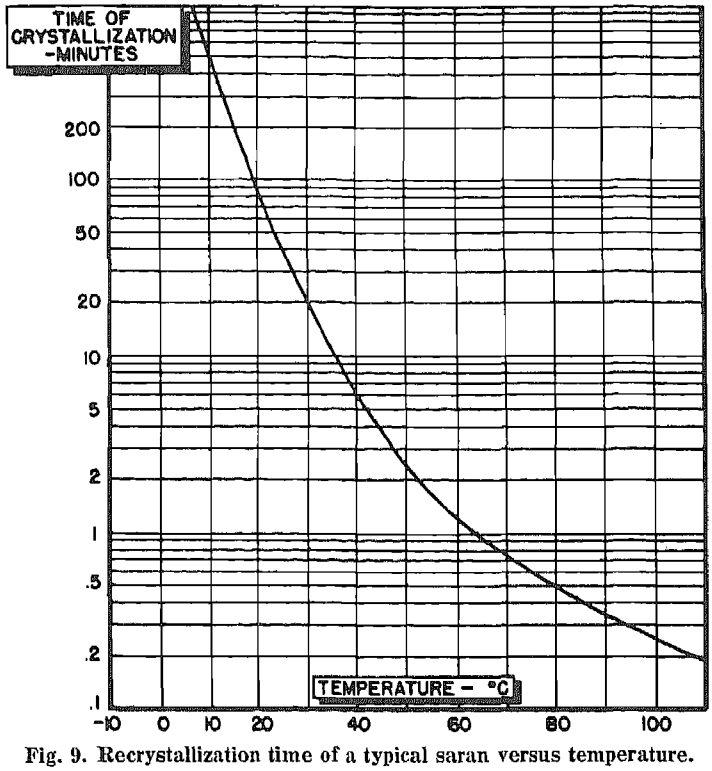


Fig. 9. Recrystallization time of a typical saran versus temperature.

A few of the applications for extruded saran that appear to be of interest include: rods for making gaskets, valve seats, ball checks, and medicinal probes; chemically resistant flexible tubing and pipe; and chemical conveyor belts.

Saran-lined pipe for the industrial transport of corrosive chemicals is fabricated by swaging to size an oversize steel pipe on an extruded saran pipe liner. In addition to its good chemical resistance and long life, this pipe is easily installed by conventional tools and requires no special support. Flanged joints using saran gaskets are used to connect lengths of pipe and fittings. Fittings are lined with injection-molded saran liners. Saran-lined pipe is not recommended for low-temperature use due to the low-temperature brittleness of these formulations.

A second method of saran fabrication is that of **injection molding.** This method makes possible the production of intricate shapes having properties similar to those obtained by extrusion. Here again, the equipment involved consists of the conventional-type injection molding machines modified only as to contact metals and designs

through the heating cylinders. The fundamentals of design include the same contact metals as listed for extrusion, strict streamlining, and the reduction of the thickness of plastic sections in the heating zones. Conventional injection molding die designs and die metals can be used.

The injection molding of saran is unique. With other commercial thermoplastics, the use of cold molds hastens the cooling of the molded parts and shortens the cycle. With saran, the reverse is true. Cold dies produce soft, flexible, amorphous pieces. Rapid hardening is accomplished by heat treatment to produce recrystallization. This is done by using heated dies. When injection molding heavy saran sections, heated dies allow the piece to retain its heat and thus rapidly recrystallize. Under these conditions saran can be ejected from the mold at temperatures as high as 100°C. in a strain-free, warp-free, dimensionally stable form. This promotes very rapid cycles with heavy sections. In fact, saran moldings have been produced with quarter-inch sections in a 17-second cycle.

Injection-molded saran played a part in national defense. Many of its applications were replacements of metals and not of other thermoplastics. Comparative tests showed that, in many instances, saran was the only material that would satisfy the industrial requirements for the replacement of such strategic materials as nickel, aluminum, stainless steel, and rubber in applications requiring chemical resistance.

In addition to the above uses, injection-molded saran can be used in the more familiar types of plastic applications which make use of its mechanical properties, exceptional chemical resistance, and attractive colors.

Saran can be **compression molded,** differing from other thermoplastic materials only in that it requires the same selection of metals for the dies as listed for hot zones in extrusion equipment. However, like other thermoplastics, the economic considerations usually favor injection molding over compression molding.

A fourth method of saran fabrication, that of **crystal orientation,** brings out the unusual properties of saran. The oriented form is produced by extrusion, subsequent plastic deformation as by stretching, and heat-treatment. It is thus possible to obtain continuous extrusions of monofilament, tape, or film having exceptional properties. While the method is not complex, it does require special control and careful attention to the techniques involved.

In the production of oriented saran extrusions, the molten amorphous plastic is extruded in the shape of the desired section into a water bath where rapid cooling prevents recrystallization from taking place. The cooled extrusion will then remain in the amorphous or supercooled state for a sufficient period of time to permit cold-working or orienting operations to be carried out. The orientation process provides a method of effecting a plastic deformation and partial recrystallization of the shaped, supercooled material.

Figure 10 shows a typical saran monofilament extrusion and orienting process. The molten saran may be extruded from a circular strand die into a cool water bath where it is supercooled. The supercooled strands are gathered by a guide shoe and led to the take-off rolls of the orienting section. Several wraps around the smooth take-off rolls is sufficient to provide a positive uniform withdrawal of the strands from the extrusion unit. The gathered strands are then wrapped several times around the orienting rolls which have a linear speed about four times as fast as the take-off rolls. Due to the difference in roll speeds, the strands are elongated under controlled conditions between the take-off and orienting rolls. During this mechanical stretching, a partial

recrystallization of the saran and orientation of the crystallites along the major axis of the strands take place. The reduction in cross-sectional area is approximately proportional to the elongation. The ultimate size and uniformity of the filaments is governed by the speed and uniformity of the withdrawal rate. The oriented filaments are then separated and led to individual spools on the spooling unit. Heat-treatment after or during stretching may be used to affect the degree of crystallization desired and thus control the properties of the oriented filaments.

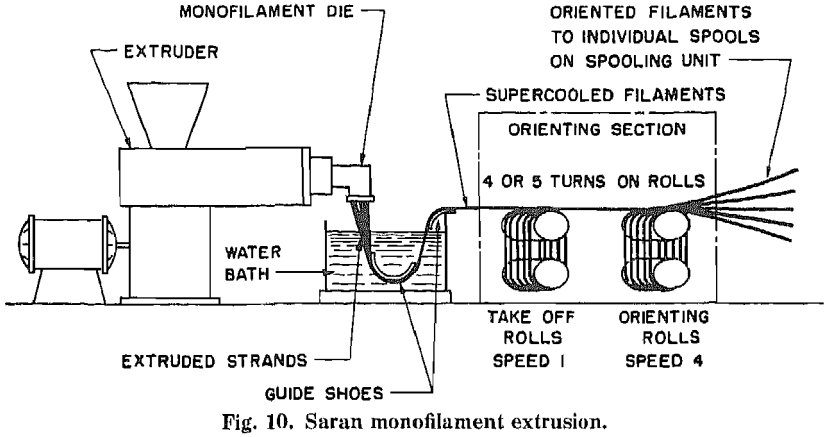


Fig. 10. Saran monofilament extrusion.

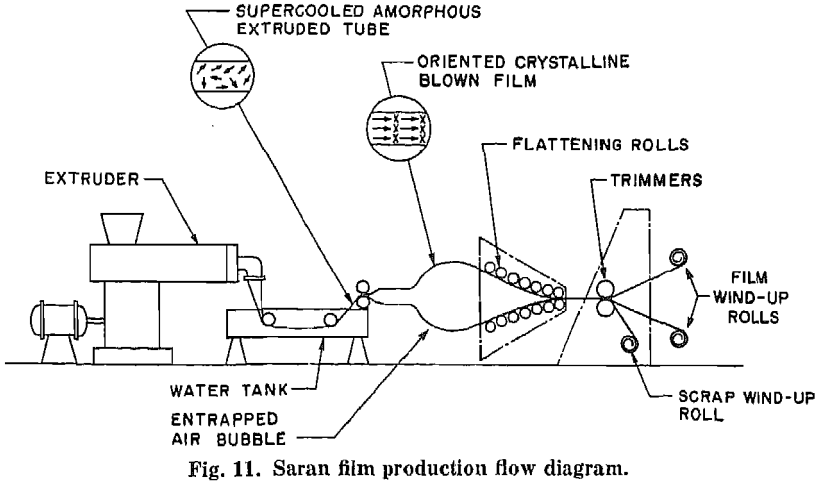


Fig. 11. Saran film production flow diagram.

The above method produces orientation in a single direction with resulting unidirectional properties of high tensile strength, great flexibility, long fatigue life, and good elasticity which are particularly desirable for small monofilaments where the load is along the longitudinal axis. In larger, noncircular sections such as tapes and ovals, the desired degree of transverse orientation can be realized and accompanying transverse properties controlled through the introduction of other factors in the process. For example, a rolling operation incorporated after the quenching step produces some flattening and transverse orientation of the strand with a resultant increase in transverse strength.

Saran monofilaments and fine fibers have contributed many useful properties to the textile industry. Among them are long life, low moisture absorption, chemical resistance, ease of cleaning, fire resistance, insect resistance, flex life, and bright built-in colors. Woven monofilament fabrics, produced on standard textile equipment, have been used in many varied home furnishing and industrial applications. In the home furnishing field, saran is used for upholstery webbing and drapery fabrics. Fine saran fibers are used in carpeting. Industrial uses for saran fabrics include automobile primary upholstery and seat covers, filter cloths, fish nets, and transportation seating. Other uses include insect screening, doll hair, and manikin wigs. See also *Textile fibers (acrylic and vinyl)*, Vol. **13**, p. 836.

Another orientation process is used in the production of saran film for industrial and household packaging use. The household film is called Saran Wrap. Saran film is a transparent and flexible thermoplastic possessing outstanding properties which make it exceptionally well suited for packaging foods, pharmaceuticals, chemicals, and other products. This film is highly impermeable to water vapor and most gases, thus making it an ideal transparent barrier for difficult packaging applications. It is resistant to and unaffected by most chemicals and consequently finds use as a cap-liner material in the closure industry.

Saran film is made by supercooling an extruded tube and subsequently orienting it in a continuous process. Figure 11 shows a saran film production flow diagram. In starting extrusion, air is injected into the supercooled amorphous tube after it leaves the water tank. This forms an entrapped air bubble in the tube. Once the process is started, this entrapped air bubble remains stationary while the extruded tube is oriented as it passes around the bubble. The resulting film is oriented in both longitudinal and transverse directions giving it excellent tensile strength, elongation, and flexibility, as well as transparency.

The properties of a one-mil saran film are given in Table IV. Other properties of interest include gas transmission rates and dimensional stability.

A one-mil saran film gives the following dry-gas transmission rates at 77 °F. and 760 mm. Hg in cubic centimeters per 100 square inches per 24 hours: CO_2, 2.4; N_2, 0.11; O_2, 0.56; H_2, 13.4; He, 33.0; Air, 0.15; Freon F-12, negligible.

Saran films, being highly oriented in the process of manufacture, exhibit some shrinkage when exposed to higher than normal temperatures. This may be desirable in some instances; for example, the heat-shrinking of overwraps on packaged items. It may also present a drawback in some applications; for example, in printing and laminating processes. In this case, preshrinking operations can be performed which minimize the residual shrink in the film.

The electronic or dielectric seal is the most satisfactory type for sealing saran film to itself. The bond strength of the electronically fused weld equals the strength of the base film. The heat-sealing temperature of saran film is between 280 and 300 °F. Heat sealing with hand or hot plate sealers will give a "peelable" seal which is satisfactory for sealing airtight overwraps, although the material may not be actually fused. Impulse sealers, solvent- and cement-type seals, and mechanical closures have been used with success. The "clinging" property of Saran Wrap, due to the combination of flexibility, smooth film surface, and static effects, provides a suitable closure for refrigerator dishes and loose overwraps.

Saran film can be printed by all of the usual methods employed in roll printing including rotogravure, aniline or Flexographic, letterpress, and so-called roller printing

with the aid of special inks. Modified bag-making machinery is available for the automatic production of saran film bags for the packaging industry.

Saran finds many uses in the field of **plastic coatings;** the saran used is a copolymer of vinylidene chloride and acrylonitrile, and solvent and latex processes are applicable.

The *solvent process* of applying coatings (saran lacquers) has been used satisfactorily in producing corrosive-resistant tanker and tank-car linings for the transport of refined

TABLE IV. Properties of a One-Mil Saran Film.

Property	Value
Sp.gr.	1.68
Area factor, sq.in./lb.	16,300
Water vapor transmission, g./100 sq.in./24 hr. at 100°F. and 90% r.h.	0.20
Water absorption	Negligible
Scaling temp., °F.	280–300
Burning rate	Self-extinguishing
Sp.heat, B.t.u./(lb.)(°F.)	0.32
Thermal conductivity, B.t.u./(sec.)(sq.ft.)(°F./in.)	1.8×10^{-4}
Resistance to heat, intermittent	Up to 200°F.
Resistance to heat, continuous	Up to 140°F.
Resistance to cold	Good flex at 0°F.
Tensile strength, p.s.i.	7,000–15,000
Elongation, %	20–40
Bursting strength, p.s.i. (Mullen)	35
Tear strength, g. Elmendorf	10–20
Folding endurance, M.I.T., 1-kg. load	500,000
n_D^{25}	1.602
Transmission of white light, %	90
Ultraviolet cutoff, A.	3000
Transmission of infrared, %	88
Resistance to sunlight	Good
Dielectric constant	
At 10^2 cycles	4.9–5 3
At 10^3 cycles	3.9–4.5
At 10^6 cycles	3.4–4.0
Per cent power factor	
At 10^2 cycles	3.5–4.5
At 10^3 cycles	5.2–6.3
At 10^6 cycles	3.9–4.5
Breakdown voltage, volts/mil	3,000–5,000
Surface resistivity, ohms	10^{12}–10^{16}
Volume resistivity, (ohm-cm.)	10^{12}–10^{16}

petroleum products such as gasoline. Brushed or sprayed in layers to a thickness of 0.008 in. on mild steel tanks and then air dried, these saran coatings provide unexcelled protection against the corrosive action of gasoline and sea water in tanker hulls. With periodic touch-ups every four years, the life of these coatings is extended indefinitely (2).

Saran lacquers are used in coating cellophane on both sides to make coated packaging films which combine saran's low water-vapor transmission, strength, dimensional stability, and chemical resistance with cellophane's excellent handling proper-

ties on packaging machinery. Paper coatings, dip coatings, and sprayed packaging are other applications for saran lacquers.

Saran *latexes* are mainly used in paper coating and specialty paint applications. These latexes permit the formulation of high-solids, low-viscosity, fast-drying, nonfoaming, solvent-free coating compositions that may be easily and readily applied by roller, doctor blade, spray, dip, and brush coating. The use of surface active agents and plasticizers in the manufacture of these aqueous dispersions alters certain properties of the deposited film, such as moisture-vapor transmission. However, the physical properties of coatings deposited from these latexes compare favorably with those obtained from saran lacquer systems.

In the latex form, the saran is present as submicroscopic particles that must fuse together when the water evaporates in order to form a film. The addition of plasticizers during manufacture makes such latexes film-forming under normal drying conditions. The surface active agents used and unique method of manufacture of these saran latexes result in a product with an unusually high surface tension and a natural resistance to foaming. This is exactly opposite to the normal behavior of most latexes and permits the manufacture of nonfoaming latex coating compositions with excellent leveling characteristics.

Saran latexes deposit smooth, transparent, tough, glossy films on air drying. The use of a high-temperature fusion step at or near the end of the drying cycle will result, however, in improved film properties. Initially, films from the latexes are almost colorless. Normal aging in light will result in a darkening of the films. Since this darkening is not accompanied by a great loss in the physical properties of the films, the latexes may be used for all types of applications, both indoor and outdoor, except where color retention is the prime requisite. The amount of darkening is sufficient to cause discoloration of white and pastel coatings, but not enough to be objectionable for most other colors.

The performance of saran latexes in industrial maintenance paints, where good resistance to oils, chemicals, solvents, and moisture is needed, has been very good. The good abrasion resistance of saran latex coatings is being utilized in the formulation of long-wearing oil- and grease-resistant floor and masonry paints. Other commercial applications include paper coatings, adhesives, textile coatings, spray packaging, and dip coatings.

Bibiliography for Vinylidene Chloride

(1) Berger, H., *Kunststoffe*, **30**, 35–37 (1940).
(2) Cranmer, W. W., *Corrosion*, **8**, No. 6, 195–204 (1952).
(3) Fuller, C. S., *Chem. Revs.*, **26**, 143–68 (1940).
(4) Goggin, W. C., and Lowry, R. D., *Ind. Eng. Chem.*, **34**, 327–32 (1942).
(5) Houwink, R., *Physikalische Eigenschaften und Feinbau von Natur- und Kunstharzen*, Akadem. Verlagsgesellschaft, Leipzig, 1934.
(6) Ostromislenski, I., *J. Russ. Phys. Chem. Soc.*, **48**, 1132–51 (1916).
(7) Reinhardt, R. C., *Ind. Eng. Chem.*, **35**, 422–28 (1943); in J. Alexander, ed., *Colloid Chemistry, Theoretical and Applied*, Reinhold, N.Y., 1943.
(8) Staudinger, H., Brunner, M., and Feisst, W., *Helv. Chim. Acta*, **13**, 805–32 (1930).
(9) Staudinger, H., and Feisst, W., *Helv. Chim. Acta*, **13**, 832–42 (1930).
(10) Brit. Pat. 477,532 (Jan. 3 1938), I. G. Farbenind.
(11) Brit. Pat. 525,048 (Aug. 20, 1940), Clarke (to Imperial Chemical Ind.).
(12) Brit. Pat. 533,142 (Feb. 6, 1941), Wingfoot Corp.
(13) Brit. Pat. 534,733 (March 17, 1941), W. N. Howell (to Imperial Chemical Ind.).

(14) Ger. Pat. 529,604 (July 15, 1931), I. G. Farbenind.
(15) U.S. Pat. 2,029,410 (Feb. 4, 1936), W. H. Carothers, A. M. Collins, and J. E. Kirby (to Du Pont).
(16) U.S. Pat. 2,121,009; -010; -011; -012 (June 21, 1938), E. C. Britton and W. J. LeFevre (to Dow Chemical Co.).
(17) U.S. Pat. 2,136,333; -334 (Nov. 8, 1938) and 2,160,944 (June 6, 1939), G. H. Coleman and J. W. Zemba (to Dow Chemical Co.).
(18) U.S. Pats. 2,136,347; -348; -349 (Nov. 8, 1938), R. M. Wiley (to Dow Chemical Co.).
(19) U.S. Pat. 2,160,903 (June 6, 1939), J. H. Reilly and R. M. Wiley (to Dow Chemical Co.).
(20) U.S. Pat. 2,160,904 (June 6, 1939), J. H. Reilly and R. M. Wiley (to Dow Chemical Co.).
(21) U.S. Pat. 2,160,931 (June 6, 1939), R. M. Wiley (to Dow Chemical Co.).
(22) U.S. Pat. 2,160,932 (June 6, 1939), R. M. Wiley (to Dow Chemical Co.).
(23) U.S. Pat. 2,160,936 (June 6, 1939), J. H. Reilly and C. R. Russell (to Dow Chemical Co.).
(24) U.S. Pat. 2,160,940; -941; -942 (June 6, 1939); E. C. Britton, C. W. Davis, and F. L. Taylor (to Dow Chemical Co.).
(25) U.S. Pat. 2,160,943 (June 6, 1939), E. C. Britton and C. W. Davis (to Dow Chemical Co.).
(26) U.S. Pat. 2,160,945 (June 6, 1939), R. M. Wiley (to Dow Chemical Co.).
(27) U.S. Pat. 2,160,946 (June 6, 1939), E. C. Britton and F. L. Taylor (to Dow Chemical Co.).
(28) U.S. Pat. 2,160,947 (June 6, 1939), R. C. Reinhardt (to Dow Chemical Co.).
(29) U.S. Pat. 2,160,948 (June 6, 1939), R. M. Wiley, F. N. Alquist, and H. R. Slagh (to Dow Chemical Co.).
(30) U.S. Pat. 2,183,602 (Dec. 19, 1939), R. M. Wiley (to Dow Chemical Co.).
(31) U.S. Pat. 2,215,379 (Sept. 17, 1940), L. B. Sebrell (to Wingfoot Corp.).
(32) U.S. Pat. 2,232,933 (Feb. 25, 1941), R. M. Wiley and J. E. Livak (to Dow Chemical Co.).
(33) U.S. Pat. 2,233,442 (March 4, 1941), R. M. Wiley (to Dow Chemical Co.).
(34) U.S. Pat. 2,235,782 (March 18, 1941), R. M. Wiley (to Dow Chemical Co.)
(35) U.S. Pat. 2,238,020 (April 8, 1941), A. W. Hanson and W. C. Goggin (to Dow Chemical Co.).
(36) U.S. Pat. 2,245,742 (June 17, 1941), C. H. Alexander and H. Tucker (to B. F. Goodrich Co.).

D. R. GRAY

VINYL ETHER, $(CH_2:CH)_2O$. See *Anesthetics*, Vol. **1,** p. 906; *Stimulants and depressants of the nervous system*, Vol. **13,** p. 8.

VINYL ETHERS. See *Reppe chemistry*, Vol. **11,** p. 649.

VINYL FIBERS. See *Textile fibers, synthetic*, Vol. **13,** pp. 811, 817, 824.

VINYLIDENE CHLORIDE, $CH_2:CCl_2$. See *Vinyl compounds (vinylidene chloride)*.

2-VINYLPYRIDINE, $C_5H_4NCH:CH_2$. See *Pyridine and pyridine bases*, Vol. **11,** p. 291.

1-VINYL-2-PYRROLIDONE, $C_4H_3N(CH:CH_2)O$. See *Plasma expanders*, Vol. **10,** p. 759; *Pyrrole and pyrrole derivatives*, Vol. **11,** p. 346; *Reppe chemistry*, Vol. **11,** p. 656.

VINYLTOLUENE, $CH_3C_6H_4CH:CH_2$; **VINYLXYLENE,** $(CH_3)_2C_6H_3CH:CH_2$. See "Styrene homologs" under *Styrene*, Vol. **13,** pp. 141, 144.

VIOLACEIN, $C_{24}H_{28}N_6O_7$. See *Antibiotics*, Vol. **2,** pp. 26, 30.

VIOMYCIN, $C_{18}H_{31-33}N_9O_8$. See *Streptomyces antibiotics (viomycin)*, Vol. **13,** p. 108.

VIRIDIN, $C_{20}H_{16}O_6$. See *Antibiotics*, Vol. **2,** pp. 29, 35.

VIRUSES. See *Microorganisms*, Vol. **9,** p. 86; *Vaccines*.

VISCOMETRY

Viscometry is concerned with the measurement of flow properties of substances, and hence is a branch of rheology (*q.v.*). In the measurement of viscosity it is necessary to distinguish Newtonian, or true viscous flow, and non-Newtonian flow. Newtonian flow is the irreversible deformation of fluids that occurs in such a manner that the rate of strain in shear is proportional to the shearing stress. Fluid flow may exhibit a number of deviations from this behavior and may include elements of elasticity (see *Rheology*). This article will deal with the measurement of Newtonian viscosity, although some of the instruments discussed can be used also to measure nonviscous elements such as plasticity and elasticity.

Principles

Newton's Law. Viscosity is the internal friction of flowing substances. It can be measured readily under conditions of lamellar flow. Lamellar flow, or laminar flow, is such that the flow of liquid can be considered to consist of thin planes of laminae flowing past each other at different velocities. When the flow does not conform to this pattern it is called turbulent. Laminar flow is usually represented by imagining the behavior of a liquid separating two parallel plates, one of which is stationary, while the other is moving with constant velocity past it in its own plane. In order to keep the velocity constant, a force must be applied to the moving plate which Newton assumed to be proportional to the area of the plates and to the velocity gradient of the fluid between the plates:

$$f \propto Av/h = \eta\, Av/h \tag{1}$$

$$\eta = fh/Av \tag{1a}$$

where f = force; η = viscosity coefficient; h = film thickness; A = area of plate; and v = velocity of plate. The proportionality constant is characteristic of a "normal" fluid at given pressure and temperature, and is called the viscosity coefficient or, for short, the viscosity of the fluid. The dimensions are seen to be η = g./cm.-sec. = dyne-sec./sq.cm.-poises. Viscosity, then, can be measured by observing any one of the variables of equation (1a) while the others are held constant at a known level.

The definition of absolute viscosity according to Newton's law involves the measurement of a tangential force acting on a moving plane. This is done in practice in rotational and oscillational viscometers. The former, or Couette-type viscometers, are based on Newton's law, and the mathematical treatment is far simpler with this type of system than with the oscillational type. However, it is difficult to provide an instrument with uniform rotation and as free from vibration and eccentricities as required for precise measurement. It is easier to construct a system that is made to oscillate about a mean position and to measure its response to the viscous resistance it encounters.

Poiseuille's Law. Laminar flow also occurs when fluids flow through tubes with moderate velocities. The thin layer of fluid in contact with the tube wall is probably stationary; the next layer flows slowly, and the adjacent layer faster. The fluid then flows as if it consisted of many thin concentric cylinders, each moving with a constant velocity which increases from the wall toward the center of the tube. Poiseuille studied the flow in capillaries and found that the volume of liquid passing through a

capillary in unit time was proportional to the pressure, to the fourth power of the radius of the tube, and inversely proportional to the length of the tube:

$$\frac{v}{t} = K\frac{pr^4}{l} \tag{2}$$

where p = pressure difference between tube ends; r = radius of tube; v = the total volume of liquid flowing; l = length of tube; t = time of flow; and K = proportionality constant. On the basis of this relation, other physicists (Wiedeman, Hagenbach), developed what is known as Poiseuille's law:

$$\eta = \frac{\pi r^4 pt}{8vl} \tag{3}$$

In this derivation it is assumed that v/t is small and that the velocity with which the liquid leaves the tube is negligible. In practice this is not true and appropriate corrections have to be made.

In the measurement of flow through capillaries, the density of the liquid enters into the relationships more immediately since the pressure term in equation (3) is frequently represented by the gravitational pull of the column of liquid being measured. The time of passage of liquids through many Ostwald-type viscometers is approximately proportional to the ratio of the viscosity of a liquid to its density under the same conditions, and this ratio is known as *kinematic viscosity*:

$$\nu = \frac{\eta}{d_t} \tag{4}$$

where ν = kinematic viscosity at temperature t; η = absolute viscosity at temperature t; and d_t = density of the liquid at temperature t. The kinematic viscosity is a term of basic importance in fluid dynamics. Since this quantity is immediately and quite precisely observable with relatively simple equipment, the concept and measurement of kinematic viscosity has assumed great importance in industrial activities as well as in the theoretical considerations mentioned.

Stokes's Law. If a body is moved through a fluid, the fluid contiguous with the body can be considered as having zero velocity with respect to the solid; adjacent layers are set in motion by the viscous drag as in the systems discussed previously. By using the principles of hydrodynamics it is possible to calculate the frictional forces due to viscous drag on bodies having simple shapes. Stokes in 1845 derived the relation pertaining to the motion of a sphere:

$$f = 6\pi r v \eta \tag{5}$$

in which f is the force causing the sphere to move through the fluid at constant velocity, v, and r is the radius of the sphere. If the sphere is allowed to fall freely through a fluid, the sphere will be accelerated until the viscous force exactly balances the force due to gravity, and:

$$6\pi r v \eta = \frac{4}{3}\pi r^3 (d_s - d_f)g \tag{6}$$

where d_s = density of the sphere and d_f = density of the fluid. From this equation we obtain the usual form of the Stokes equation

$$\eta = \frac{2r^2(d_s - d_f)g}{9v} \tag{7}$$

This relation can therefore be used, given the radius of the sphere and the densities involved, to determine the viscosity of a fluid by observing the velocity of fall of the body in the fluid. This applies to many systems, such as liquid drops falling in gaseous mediums, or solids in liquids, and others. The former system figured in the determination of Avogadro's number by Perrin (1908); the latter is commonly used in the determination of the viscosities of liquids in such instruments as the Höppler falling-ball viscometer and others.

Effect of Variables

Temperature. So far the attempt has been made to speak in general terms of "fluids," which include any flowing body, gaseous, liquid, or quasi-solid. In their temperature dependence of viscosity, however, gases differ from liquids. The viscosity of gases increases with increasing temperature, while that of liquids decreases. In gases an increase in temperature results in a larger mean free path and in an increased average energy of molecular collisions. In liquids, where the molecules are very close together, the overriding effect of temperature is to decrease viscosity by increasing the distance between molecules, thus lessening the number of collisions.

The viscosity of gases can be computed from the kinetic theory, at least to the extent to which they approximate ideality. The viscosity should be proportional to the kinetic energy of the molecules, and thus to the square root of the absolute temperature. Actually the increase in viscosity is more rapid than calculated from the foregoing statement. The assumption that the molecules do not influence each other, on which this relationship is based, therefore cannot be accepted, and modified relationships have been formulated, of which that of Sutherland is very useful over a large temperature range:

$$\eta' = \eta''(T'/T'')^{1/2} \cdot \frac{[1 + (C/T'')]}{[1 + (C/T')]} \tag{8}$$

where η', η'' = viscosities at two temperatures, T' and T'' in °K. and C = a constant. The viscosities of the gas are measured at two temperatures, the constant C is calculated, and the viscosity can then be computed for any temperature. For very low temperatures, use is made of Chapman's formula:

$$\eta' = \eta'' (T'/T'')^{1/2} \cdot \frac{[1 + (C/T'') - (C'/T'')^2]}{[1 + (C/T') - (C'/T')^2]} \tag{9}$$

No theory of liquids is available that will permit a similar computation of the viscosity of a liquid and its temperature coefficient. A number of equations, however, have been developed on the basis of some simple basic assumptions. Andrade (1) imagined that the molecules of a liquid were continually associating and dissociating, transferring momentum in the process of associating. The higher the temperature, the less the tendency to associate; from this basis he derived, following Boltzmann's theory of association, the formula:

$$\eta = Be^{b/T} \tag{10}$$

where B and b are constants to be determined empirically.

An elaboration developed by Andrade to allow for the change of volume, v, and of potential energy with temperature gave:

$$\eta v^{1/3} = Ae^{c/vT} \tag{11}$$

c is related to van der Waals' constant a since the potential energy of a van der Waals' fluid is a/v. These formulas hold remarkably well for many nonassociated liquids, but not for those where the coordination changes with temperature, such as tertiary alcohols or water.

In industry, the temperature dependence of viscosity can become extremely important. Where the performance of a product depends on viscosity, and where it is applied over a substantial temperature range, its temperature coefficient is likely to determine, or at least to figure in, the value of the material. This is true for lubricating oils and greases. For such groups of products special relationships and charts have been worked out empirically. Among the best known are the A.S.T.M. charts (A.S.T.M. D341–43) and the viscosity index (11) for lubricating oils. These relations can be used to obtain by interpolation, and over certain ranges by extrapolation, the viscosity of an oil at any temperature after its viscosity has been determined at two selected temperatures. In addition the charts can be used to determine approximately the viscosity of a mixture of two oils if the viscosities of the unblended oils are known. The mixture rules will be mentioned again later.

The temperature dependence of viscosity is also a strong factor in the design and *operation of instruments for measuring viscosity.*

Pressure. There surely exists a relation between viscosity and specific volume of liquids although no theoretical representation so far has been successful. Since pressure influences the specific volume one may expect that it also affects viscosity. Bridgman (8) has studied viscosities at pressures up to 12,000 atm. and found that the viscosities of nearly all liquids are direct functions of the pressure. The rate of increase appears to be greater with more complex molecules. Water behaves anomalously: at temperatures below 30°C. the viscosity at first decreases, then increases with rising pressure, showing a minimum at about 1000 atm. which is more marked the lower the temperature. At temperatures above 30°C. water does not show this minimum, but behaves like other liquids. The viscosities of gases should be independent of pressure, according to the kinetic theory. Generally this condition holds as long as the pressure is not so low that the mean free path of the molecules becomes comparable with the dimensions of the vessel, or so high that it approaches saturation pressure. This has been found true, for example, between 1 and 760 mm. pressure for air, and nearly true over much larger ranges.

Mixtures and Solutions. Many discussions on this subject can be found in the literature, but no general treatment is available. For discussion of the viscosity of polymers and their solutions, and its significance with regard to estimation of molecular weight or degree of polymerization, see *Lubricants*; *Polymers*; *Rheology*. No *a priori* statement can be made at present regarding the viscosity of mixtures on the basis of the unmixed substances. The relation so far has not been found linear in any case, frequently shows maximums, sometimes minimums, and sometimes goes from one type to the other on changing the temperature. Often anomalous behavior of the viscosity-composition isotherm reflects compound formation; determination of these isotherms, therefore, can be useful in the study of complex formation or association compounds in general.

Empirical aids for estimating the viscosity of special types of mixtures have been worked out. The A.S.T.M. viscosity index charts, for instance, may be used in making oil blends if the viscosities of the starting oils are known.

Methods of Measurement

Nearly everyone who has studied the subject of viscosity more than superficially has designed an instrument for his special requirements, or one intended to overcome some of the shortcomings of earlier designs. For this reason such a multitude of types and forms of viscometers are described in the literature that the present discussion must necessarily be incomplete. In the following sections, the various general classes of viscosity measuring apparatus will be discussed in terms of a few of the most outstanding and widely used viscometers of each type. The considerations applying to these specific examples are so common to all viscometers in the same classes that it should not be difficult to assess the qualities of other devices from the discussion. A more complete description of modern apparatus can be found in a number of reference books (4,17,28,34).

Before entering into the discussion of the viscometers themselves, the fundamental importance of temperature in viscosity measurements should be emphasized. Temperature coefficients of viscosity are normally very high, and in general they tend to be greater for materials of higher viscosity. (See Vol. **11**, p. 734.) In working with average materials a temperature control within $\pm 0.01°C.$ is required for measurements intended to be consistently accurate to within 0.1%, that is, consistently within 0.1% of the true value. For measurements in which 0.5% accuracy is sufficient, a variation of $\pm 0.05°C.$ is tolerable. The predominant role of temperature has been recognized by the principal standardizing bodies of the world, and rigid specifications for temperature control have been included in the standard methods. To further assure temperature reproducibility among laboratories, elaborate specifications for thermometers for use in viscosity measurements have been set up (A.S.T.M. E1–53).

Careful attention must be paid to the design of constant-temperature baths, particularly in regard to the elimination of temperature gradients in the bath liquid. It is not generally appreciated that a bath in which stirring is vigorous and in which the temperature at one point is controlled to within $0.01°C.$, can have stable temperature differences at other parts of the bath amounting to several hundredths of a degree. This condition is usually brought about by large heat losses through the bath walls, which are compensated by the use of a heater of small area. It can be remedied by improving the quality of the insulation, or by introducing the greater part of the compensating heat uniformly over the walls of the bath.

Another factor that is often overlooked is the necessity for the sample to equilibrate completely with the constant temperature bath. A surprising amount of time is required to reach temperature equilibrium with samples of high viscosity. In general, a bath or viscometer which is being maintained within $0.01°C.$ of a desired temperature is easily shocked by contact with a cooler or hotter object. In determining viscosities, it is good practice to avoid placing a viscometer or any other object in the constant-temperature bath while another viscometer is being equilibrated or operated.

CAPILLARY TUBE VISCOMETERS

Capillary tube viscometers are particularly convenient for measurement of the flow properties of liquids that do not exhibit a yield value or time-dependent changes in

consistency such as work hardening or softening. They are normally employed for precise measurements on Newtonian liquids in the range from about 0.01 to 100 poise. They are not convenient for use with non-Newtonian liquids because of the variation in the rate of shear with distance from the tube walls; however, when instruments are used in which it is possible to vary the pressure drop through the capillary over a wide range, the flow characteristics of non-Newtonian liquids can be deduced from the capillary measurements. The basic equations for this analysis were first published by Rabinowitsch (31), and were independently derived by Clark and Deutsch (10). Since capillary tube viscometers are not the instruments of choice for handling these systems, only their application to Newtonian liquids will be considered.

For rough work in which moderate errors can be tolerated (approximately 0.5%) the Poiseuille equation (see p. 757) is an adequate expression for flow in even very short capillaries; however, for refined work it is necessary to introduce two correction terms associated with the effects at the capillary ends. The larger effect, known as the kinetic energy correction, is added to account for the energy required to accelerate the liquid from its velocity in the inlet reservoir to its average velocity within the capillary. If the flow is steady and uniform, it can be shown that the pressure correction should be:

$$-\frac{dQ^2}{\pi^2 r^4} \text{ (for symbol definitions see below)}$$

However, accelerations and lack of steady flow conditions lead to departures in real instruments that are corrected by including a coefficient m. While it has been considered that m is a constant of a given apparatus, recent work tends to indicate that it is really a function of Reynolds number. The second correction is an allowance for viscous resistance encountered by the liquid as a result of velocity gradients in the converging stream entering the capillary. It is normally expressed as a hypothetical increase in capillary length which is proportional to the capillary radius. With the two correction terms added, the complete equation for fluid flow through a capillary becomes

$$\eta = \frac{\pi r^4 p}{8Q(l + nr)} - \frac{mdQ}{8\pi(l + nr)} \tag{12}$$

where η = the liquid viscosity in poise; r = the capillary radius in cm.; p = the pressure drop through the capillary tube in dynes/sq.cm.; Q = the rate of flow of liquid through the tube in cu.cm./sec.; l = the length of the capillary tube in cm.; d = the liquid density; m = the kinetic energy coefficient; and n = the so called "Couette" constant, such that nr is the hypothetical increase in capillary length needed to account for convergence friction.

Absolute and Standard. A viscometer is considered to be an absolute instrument if its calibration constants are obtained solely from its dimensions and its operating characteristics. While it is theoretically possible to use any capillary viscometer as an absolute instrument, it is extremely difficult to obtain accurate results unless it is constructed with extreme care and in such a manner that the modified Poiseuille equation (12) can be easily applied. The recent determination of the viscosity of water at 20°C. by Swindells *et al.* (37) serves as an excellent example of the apparatus and technique for absolute measurements of the highest accuracy using capillaries. A schematic diagram of their apparatus is shown in Figure 1. Test liquid (water)

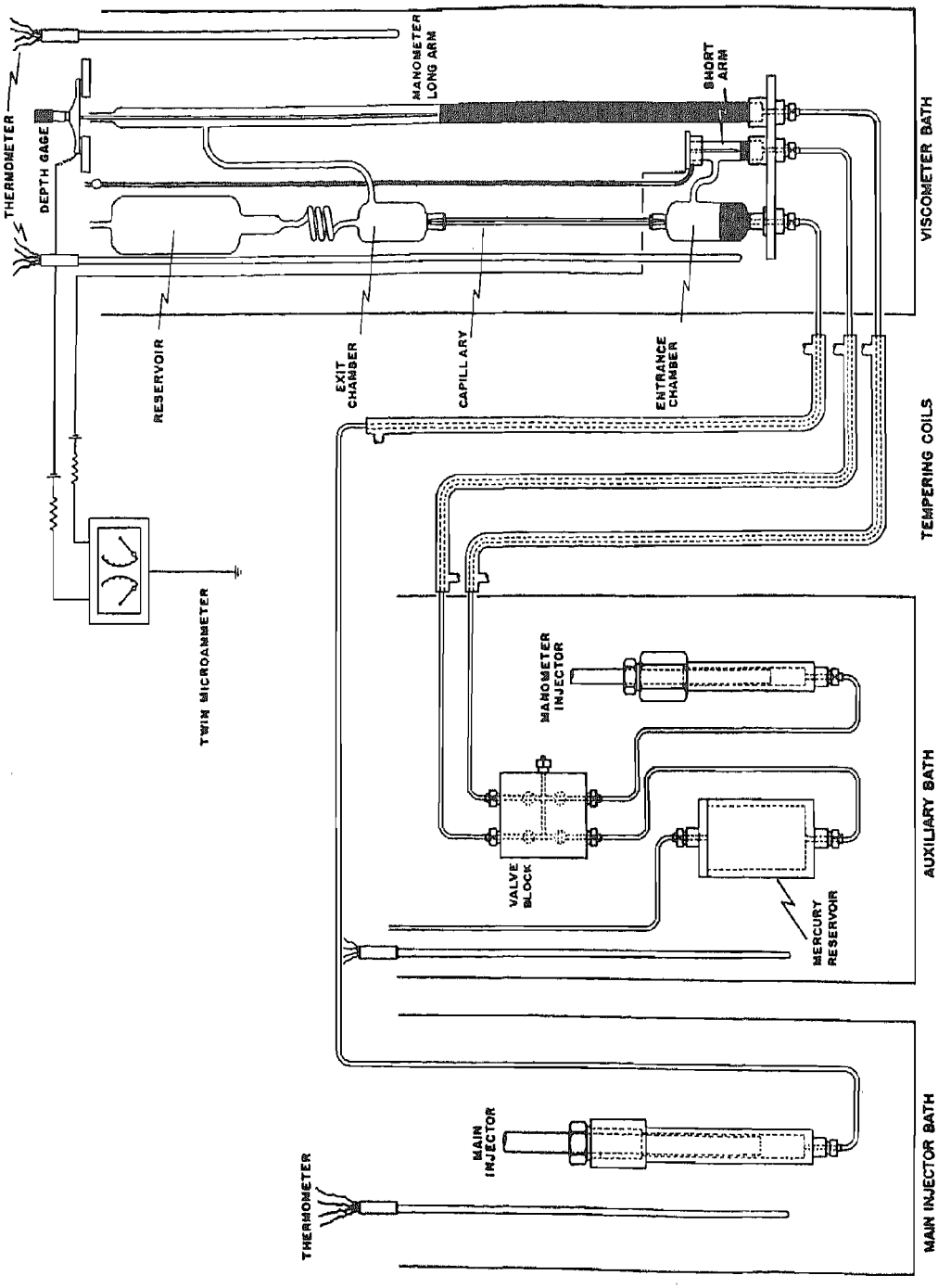


Fig. 1. National Bureau of Standards apparatus for absolute viscosity measurement (37).

from an injector was forced through the capillary at known rates, and the pressure drop across the capillary tube was measured by means of a mercury manometer system. The following considerations were essential to the attainment of accurate results: (*1*) temperature control within ±0.004°C., (*2*) constant and accurately known delivery of liquid by the injector, (*3*) accurate and sensitive measurement of the pressure drop across the capillary, (*4*) extremely precise measurements of capillary dimensions including such factors as ellipticity of cross section, (*5*) special experimental and extrapolation procedures to account for the necessary kinetic energy and "Couette" corrections.

In general, absolute measurements are made only for special standardizing or research purposes. Several instruments for industrial purposes could, however, be classed as absolute capillary viscometers, although their accuracy is rather poor. The Saybolt, Engler, and Redwood instruments, which are extensively used for routine testing of oils, are short-capillary instruments in which the primary calibration lies in the specified dimensions of their various parts. It has become common to refine the individual instrument constants by measurements on standardizing oils in order to obtain a correction factor, so that their actual application is now rarely as absolute viscometers.

The *Saybolt viscometer* is representative of all three instruments. It has been standardized by the A.S.T.M. in forms suitable for lubricating oil measurements and for testing of fuel and road oils and is completely described in A.S.T.M. method D88–53. Essentially it consists of a brass tube fitted with a short capillary of precise dimensions at the bottom, and mounted in a suitable constant-temperature bath. The tube has an overflow weir for liquid-level adjustment at the top, and has a crude valve in the form of a cork stopper at the bottom. The tube is filled with the test liquid, allowed to come to temperature equilibrium, the weir gallery is emptied carefully, the stopper is pulled, and the number of seconds required to collect a definite volume of liquid in a vessel placed under the capillary is measured. Viscosity is normally reported simply as Saybolt Universal or Saybolt Furol seconds, but it may be converted to centistokes by means of appropriate tables (A.S.T.M. D446–53 and D666–53).

Relative. While it is extremely difficult to obtain accurate capillary viscometer constants from the dimensions and operating conditions of the apparatus, it is a comparatively easy matter to calibrate capillary instruments by standardizing with liquids of known viscosities. Comparatively simple apparatus can be used for such relative measurements. The primary reference liquid for viscometer calibrations is water at 20°C. because it is easily prepared in a pure form and its viscosity is known to a high degree of accuracy (A.S.T.M. D445–53T). The details of the calibration procedure based upon water will be discussed (see p. 764) for the most common type of capillary instrument. A number of secondary standards are available from the National Bureau of Standards and from the A.P.I. (A.S.T.M. D445–53T); these liquids provide a convenient means for calibrating viscometers for routine purposes.

Relative capillary viscometers fall into two general classes, depending upon whether the hydrostatic pressure of the test liquid itself induces the flow through the capillary or an external pressure is applied to force the liquid through the tube. The first type of instrument is more widely used and is of sufficient importance to justify a detailed description of its manipulation.

Gravity-Driven. Present day gravity-driven viscometer tubes are generally de-

rived from *Ostwald's* original design, a slight modification of which is shown in Figure 2(*a*). In use, this instrument is inverted with the tip of the capillary tube immersed in the liquid to be studied. A vacuum is applied to the wide bore tube until the meniscus is at the mark B, whereupon the tube above mark A is closed with a finger and the viscometer is set upright. Excess liquid is wiped off the outside, the finger is removed, and the viscometer is placed in a constant temperature bath. When temperature equilibrium has been established, the liquid is again returned to the upper reservoir bulb with the meniscus above the fiducial mark, either by applying vacuum at the capillary or pressure at the other tube. Finally, the vacuum or pressure is released and the time required for the liquid to flow between marks is measured.

The Poiseuille equation in the appropriate form applying to such an apparatus can be written as follows:

$$\nu = \eta/d = \frac{\pi r^4 hgt}{8V(l + nr)} - \frac{mV}{8\pi(l + nr)t} \tag{13}$$

where $\nu = \eta/d$ is the kinematic viscosity; r = the radius of the capillary; l = the capillary length; h = the mean liquid head during the measurement; V = the volume of liquid delivered from the upper reservoir bulb; t = the time required for the liquid to pass between fiducial marks; g = the acceleration of gravity; m = the kinetic energy coefficient; and n = the Couette correction coefficient.

Since these viscometers are always calibrated by direct application to reference liquids, this expression can be simplified to:

$$\nu = Ct - B/t \tag{13a}$$

where C and B are instrument constants calibrated by measurements on known materials. In general it is found that B/t is very small relative to the first term and can be neglected except for measurements on materials having viscosities less than 2 centistokes. It can be neglected for these materials if the efflux time is greater than 300 seconds.

The *calibration procedure* for the simple Ostwald viscometer is the same as that used for all later designs of this type. Accordingly, the considerations necessary for its accurate calibration and use will be described. The advantages and disadvantages of some of the later models can then be discussed in terms of the various factors affecting accuracy and precision.

For convenience in use and in calibration, it is advisable to employ a set of viscometers in which the dimensions are adjusted so that the C constants in equation (13a) for successive instruments differ by factors of about 3. For example, a typical set should include viscometers having constants, in centistokes per second, of about 0.001, 0.003, 0.01, 0.03, 0.10, 0.30, 1.0, 3.0, and 10.0. It is not advisable to attempt to use capillary viscometers having lower or higher constants; those having lower constants present excessive cleaning difficulties because of the fine capillaries, while liquids of viscosities requiring higher constants cannot be handled satisfactorily in U-tubes.

Cleaning of the tubes should be carried out with extreme care. The manner in which the test fluids wet the walls and drain during measurements depends upon wall cleanliness; in addition, the viscometers having low constants are especially sensitive to dust or small particles. It is advisable to filter all liquids and cleaning acids into the tubes. A good cleaning procedure is to wash with solvents to remove any previous

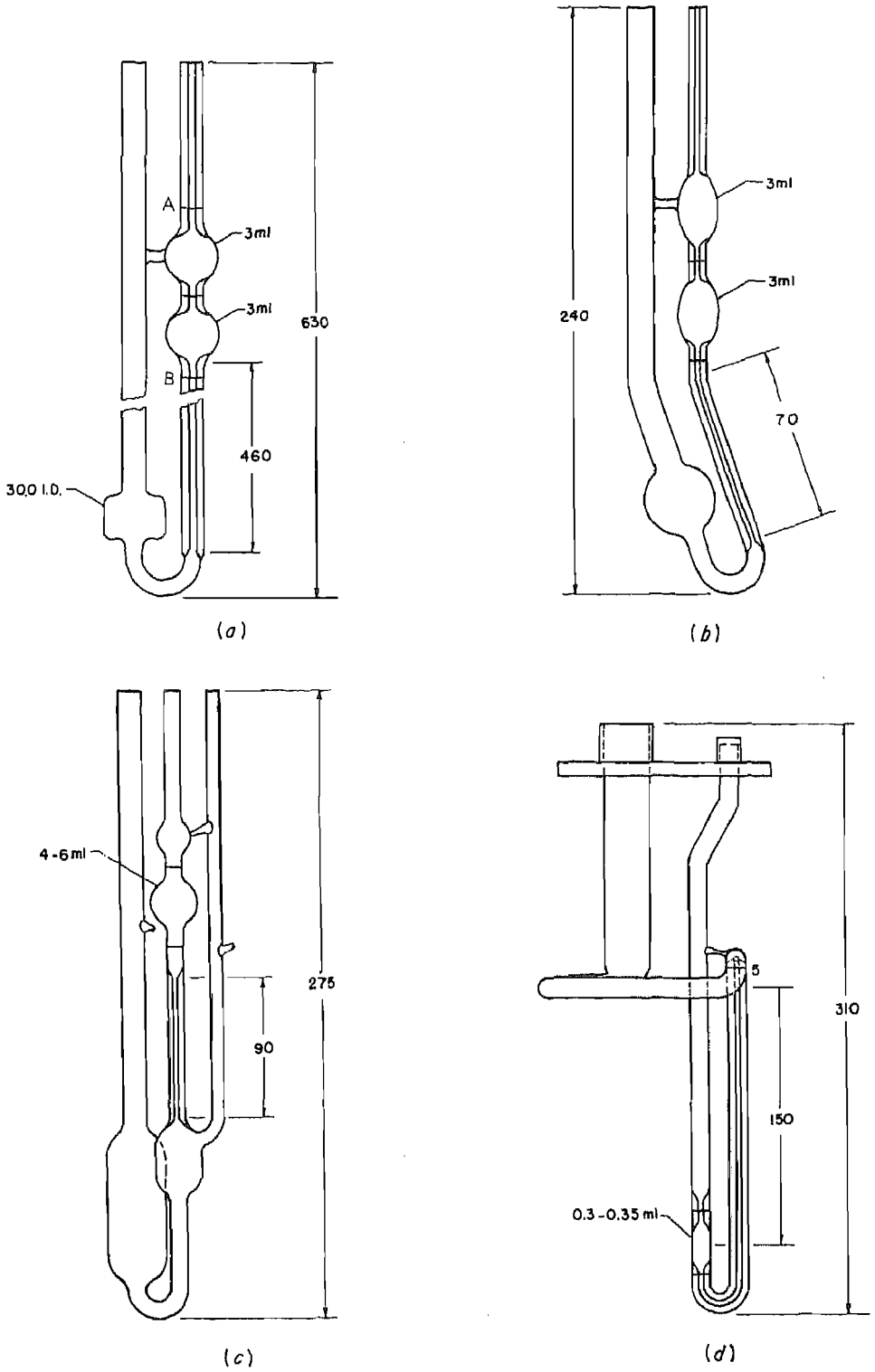


Fig. 2. Typical glass capillary viscometers: (*a*) Cannon master viscometer, (*b*) Cannon-Fenske viscometer, (*c*) Ubbelohde viscometer, (*d*) Cross arm viscometer.

liquids, remove the solvents by washing with alcohol or acetone, wash with water, and then soak in chromic acid–sulfuric acid. When the surface is clean, the acid mixture is removed by thorough washing with distilled water, and the tube is dried by drawing through a stream of filtered air. It has been found that the inner surface of the tubes is often permanently changed when used for measurements on silicone oils. For these materials it is advisable to use a separate set of viscometers calibrated especially for this purpose.

The primary method of calibration, the "step-up" procedure, requires that all of the viscometers be standardized against water at 20°C. This is only directly possible for the lowest instruments in the series; however, after these have been calibrated, they can be directly compared with the next higher viscometer using a suitable liquid of higher viscosity. This can be continued with increasingly more viscous oils up to tubes having a constant of 10 centistokes per second.

The constant B in equation (13a) is probably not a true constant owing to the variation of m with Reynolds number. For this reason it is advisable to perform the step-up procedure with a special set of "master" viscometers in which the contribution of the whole B/t term to the viscosity is less than 0.1%. Routine viscometers can then be calibrated by direct comparison with the masters. Information regarding the design of a viscometer that will serve as a master is extremely limited. In general the contribution of the B term can be reduced by making the flow volume V small, and by increasing the length; however, the minimum volume-length-ratio has not been established. It is well known that viscometers having a 3-ml. upper reservoir and a 48-cm. capillary are satisfactory.

To carry out the step-up procedure, the viscometers having constants of 0.001 and 0.003 are filled with freshly boiled distilled water and the times of flow are measured at 20°C. Appropriate corrections as discussed in the following sections are made, and the constants are calculated from the known viscosity of water. The 0.003 tube and the 0.01 tube are then filled with a light oil, such as kerosine, which will give a reasonable time of flow in both instruments. The times of flow are measured and corrected, the viscosity of the oil is calculated from the known constant of the 0.003 tube, and the constant of the 0.01 tube is calculated from the viscosity. This procedure is continued up the series. It should be noted that the measurement on water is the only one for which the temperature must be exactly 20°C. For the other measurements any constant temperature will serve, provided that appropriate corrections are made.

It is usually inconvenient to employ master viscometers for routine measurements. Therefore, after calibration of the masters, a number of sets of smaller viscometers are calibrated by direct comparison with them. By using several oils for the comparison of each routine viscometer, the constant B, which is often appreciable for short capillaries, may be evaluated.

A second method for calibration of routine viscometers is afforded by oils of known viscosities obtainable from the National Bureau of Standards and from the A.P.I. The details concerning their use are to be found in A.S.T.M. method D445–53T.

Corrections Applicable to U-Tube Capillary Viscometers. A number of corrections must be made in order to relate flow times in an Ostwald-type capillary viscometer to viscosity through equation (13). These corrections have been discussed in detail (38). A brief summary of the main factors to be considered are given below.

The viscometer itself is used as a pipet for the introduction of a standard volume of liquid. This volume affects the liquid levels in the U-tube during the test and con-

sequently the mean head. The pipetting is normally done at room temperature, which is usually different from the test temperature. The volume change on heating or cooling the pipetted liquid to test temperature must therefore be taken into account. For lubricating oils pipetted at 70°F. with a typical instrument and used at 210°F., the correction amounts to about 0.1–0.4% of the observed flow time.

Calibration relative to water (or standardizing oil) is made at a single temperature. When the viscometer is used at a different temperature, corrections must be made for changes in dimensions of the tube owing to expansion and contraction. The order of magnitude of the correction is very small and is usually combined with the correction for filling volume.

In a U-tube viscometer the driving head of liquid is opposed by the weight of the air column in the opposite arm. Since the weight of this air changes with temperature and humidity, a correction must be made. The magnitude of the correction is of the order of 0.035% of the observed time for oils when an oil of density 0.769 is run at 100°F.

In U-tube viscometers the differences in the diameters of the tubing on the two sides at various times of flow lead to a difference in the capillary rise between the two sides. This difference adds or subtracts from the liquid head and must be corrected for. The surface tensions of oils containing no surface active additives are very nearly the same so that very little error is introduced by assuming a constant surface tension effect for such oils. Special attention should, however, be given to oils containing various additives. Water differs markedly from oils, and since it is the primary reference liquid, it is essential to determine the correction for the surface tension difference between water and oils at 20°C.

The method for calculating the surface tension correction for a given viscometer is presented by Barr (5). His method, using the tables of Bashforth and Adams (6) to determine the meniscus volume and capillary rise at various points in the tube, is the only method that will yield satisfactory results. Other approximate formulas are of little use. A better means of arriving at the correction is the experimental method described by Swindells *et al.* (38). The order of magnitude of the surface tension correction when a water-calibrated tube is used on a lubricating oil stock is about 0.2–0.3% for a master viscometer. In shorter routine instruments the correction is often as high as 0.5%.

A few important sources of error in the use of Ostwald-type viscometers are the following: (*1*) Temperature fluctuations. The effects of temperature have been discussed (see p. 758).

(*2*) Drainage errors. The constants C and B of equation (13a) are only constant if the volume does not change. Fortunately, if the tubes are used with properly standardized procedures this is true. The necessary precautions have been discussed (38).

(*3*) Vertical alignment. Appreciable changes in liquid head result from the viscometer being used in a nonvertical position. The magnitude of the error has been discussed (42).

(*4*) Timing. For accurate work it is necessary to use dependable interval timers. In most areas the electrical mains are not suitable for short intervals, but if crystal or tuning fork frequency controllers are employed, electrical timers are convenient. Stopwatches are satisfactory, but they must be frequently calibrated.

(*5*) Observation errors. Errors are often introduced by irregular or thick fiducial

lines. Difficulties in observing slow transit times of the meniscus can be greatly reduced by using a small telescope focussed upon the tube. For accurate work the fiducial lines should be made very fine, and should circle the tubing in a plane perpendicular to the tube axis. Although the surface tension corrections become greater when the tubes above and below the reservoir bulb become smaller, it is advisable to keep them below 2 mm. for a 5-ml. bulb in order to achieve satisfactory precision.

(*6*) Changes in sample composition. In filling a viscometer, or in forcing the liquid into the upper reservoir, a variable amount of air may be dissolved in the liquid, causing an appreciable viscosity change. If the liquid is sucked up into the reservoir bulb using a vacuum line, light ends may be lost, causing an increase in viscosity. It is probably most satisfactory to use a carefully controlled pressure in forcing the liquid up the tube. This at least assures a reproducible amount of dissolved air and increases precision.

Modern Capillary Viscometers for Relative Measurements. The designs of viscometers used most extensively in the U.S. at present are described in A.S.T.M. method D445–53T. A few noteworthy examples are shown in Figure 2. The Cannon master-style viscometers have been shown to be excellent instruments for primary calibrations. The long capillary and small upper reservoir bulb assure a low kinetic energy correction, while the large diameter of the lower reservoir minimizes head errors due to volume changes from temperature effects or from improper adjustment of initial volume. The great length with consequent large driving head of liquid also gives rise to smaller percentage corrections for the surface tension effect and other head corrections than would be the case for shorter tubes. The Cannon-Fenske routine viscometers are constructed so that the lower reservoir is directly below the upper reservoir, a condition that has been shown to give the minimum change in head resulting from error in the vertical alignment of the viscometer. The Ubbelohde design was first proposed as a means of eliminating the surface tension correction. Barr has pointed out the fallacy in the reasoning behind this means of correcting (5); however, the instrument still has one very great advantage. In using it, a roughly measured amount of liquid is introduced and allowed to reach temperature equilibrium. The capillary, upper reservoir, and the side tube are then filled by applying pressure to the lower reservoir until the liquid is above the upper fiducial mark. When the pressure is released the liquid flows rapidly out of the large side tube and the reservoir under the capillary is emptied. The time for the liquid to flow out of the upper bulb through the capillary is then measured. By this means, the lower liquid level is made unimportant and the volume initially added to the instrument does not have to be precisely measured. Since the test liquid is added with the viscometer in the bath, the first temperature correction above can be ignored.

In measuring very dark oils, the meniscus cannot be observed through the oil film left behind as the liquid drains, it is therefore necessary to place the fiducial reservoir at the bottom of the tube and time the rise of the meniscus into the previously unwet bulb. An ingenious instrument that allows this type of measurement in addition to eliminating the need for precise volume adjustments is the small "crossarm" viscometer (see Fig. 2(*d*)). Liquid is placed in the cross arm until the level is about at line 5. After it equilibrates to bath temperature, a slight pressure causes it to siphon down through the capillary into the measuring bulb. The upper meniscus travels horizontally in the crossarm and does not therefore change the head during flow. A very rough volume adjustment assures a highly reproducible driving head.

An instrument noteworthy for its method of adjusting the liquid volume, as well as for the fact that it is a standard viscometer in Europe is the Vogel-Ossag (see Fig. 3). The inner cup of this apparatus is filled to overflowing with test liquid, the pipet assembly is screwed into place, liquid is sucked up into the pipet, and the time for the bulb to empty is determined. A similar device constructed entirely of glass is employed by the Standard Inspection Laboratory (A.S.T.M. D445–53T).

A large number of capillary viscometers for very crude control or standardization purposes are in common use. A variety of cup-type viscometers are available which are similar to the Saybolt, Engler, or Redwood instruments, but which differ slightly in dimensions or construction. The Ford cup is typical of this type (A.S.T.M.

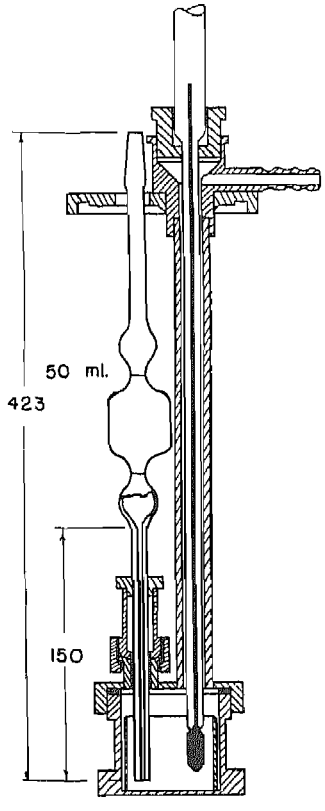


Fig. 3. Vogel-Ossag viscometer (4).

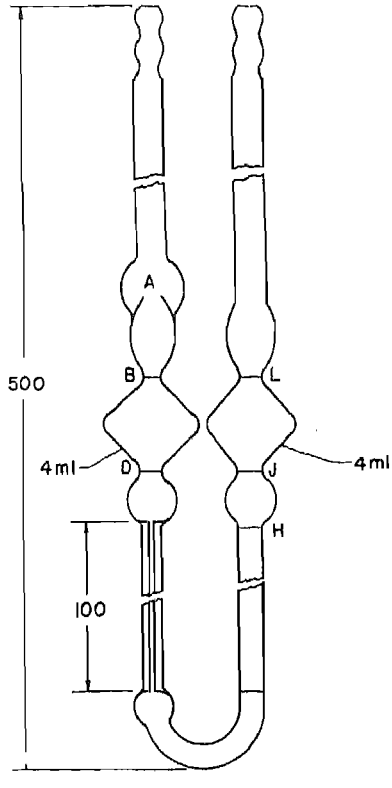


Fig. 4. Bingham pressure-driven viscometer.

D1200–52T); it was originally designed at the Ford Motor Company, but has since been redesigned to include a replaceable capillary and bottom closure. It is extensively used for examination of paints, varnishes, and lacquers. Simple pipets are convenient for a number of applications and have been used to advantage in the testing of oil and glue products. A typical instrument is the Dudley pipet which has been applied to a number of materials such as oils, dextrin, and glues (15).

Pressure-Driven. Fundamentally, pressure-driven capillary viscometers are not different from the gravity-driven type. They differ only in that a pressure large with respect to the liquid head is used to force the liquid through the capillary tube. The advantages gained are: (*1*) the absolute viscosity is determined with accuracy without

the necessity of obtaining accurate density data, (*2*) fewer tube assemblies are needed to cover a wide viscosity range since the time intervals can be adjusted by altering the applied pressure, (*3*) surface tension effects and other head corrections are lost in the large applied pressure. The disadvantages are: (*1*) they are inconvenient to use compared with the simple U-tube type gravity-driven instruments, (*2*) pressures of the required constancy are difficult to maintain, (*3*) drainage corrections needed for variations in the rate of emptying the reservoir bulbs are large and uncertain, (*4*) dissolved gas may have a considerable effect upon the liquid viscosity.

The Bingham viscometer (Figure 4) is a typical relative pressure-driven capillary apparatus. It is filled by means of a pipette, holding the level in the right limb at *H* until liquid just overflows the weir at A. A known pressure difference is applied across the two arms and the time is measured for the liquid to flow from B to D. The pressure can be reversed and the flow time measured from L to J. The use of the instrument and the necessary corrections have been completely discussed (38).

Another important pressure-driven viscometer used for the testing of greases is the S.O.D. pressure viscosimeter (30). This apparatus has been specified in A.S.T.M. method D1092–51.

ROTATIONAL VISCOMETERS

Rotational viscometers are useful over a wide range of viscosities and are particularly valuable for the study of non-Newtonian systems. They are normally employed in the range above 50 poises, although they can be used satisfactorily even for gases. For work of the highest precision (better than 0.1%) their design and construction becomes difficult; however, for routine applications where precision is less essential they are simple and convenient.

Coaxial cylinder viscometers consist essentially of two concentric cylinders separated by a thin annular layer of the liquid to be tested. One of the cylinders is rotated while the other remains stationary, producing a shearing action on the liquid. The torque required to produce rotation at a given angular velocity, or the angular velocity resulting from a given torque is measured to determine the viscosity. The fundamental equations are the following:

Stress at inner cylinder wall $= T/2\pi r^2 l$

Rate of shear at inner cylinder wall $= 2\Omega R^2/R^2 - r^2$

$$\eta = \frac{\text{stress}}{\text{shear rate}} = \frac{T}{4\pi l\Omega}\left(\frac{l}{r^2} - \frac{l}{R^2}\right)$$

where T = the torque exerted on the inner cylinder; l = the length of the inner cylinder; Ω = the relative angular velocity of the cylinders in radius per second; r = the radius of the inner cylinder wall; and R = the radians of the outer cylinder wall.

Viscometers of this type are well suited for absolute measurements because of the simple relationship between viscosity and their dimensions and operating characteristics. They are also widely used for relative measurements.

Although the principle is simple, it is difficult to construct a coaxial cylinder or Couette viscometer for precise and accurate absolute measurements. The greatest problem lies in the elimination of end effects resulting from friction on the bottom or top of the inner cylinder. A number of different techniques have been used for this purpose; Couette and others placed guard rings above and below the inner cylinder (see Fig. 5). Mooney and Ewart (24) used a conical end on the cylinder and corrected

mathematically for the effect. Ford and Arabian (19) used an instrument that eliminated end effects altogether in the study of asphalts; however, their apparatus was not suitable for liquids of appreciably lower viscosity. Gurney (16), Searle (35), Lillie (20), and Lindsley and Fischer (21) varied the lengths of the annular space, keeping the size and operating characteristics of the ends constant, thus allowing an experimental determination of the end effects correction for each sample. Lindsley and Fischer (21) have given a brief review and discussion of the problem. Because of the difficulties inherent in all of the correcting methods, the most common approach is simply to make the cylinder as long as possible in order to make the end effects small. A good design, in which the ratio of cylinder wall area to end area is a maximum, is that of Örne (27), in which the inner cylinder rotates in an annular space between two other cylinders. This device is self-centering and is suitable for studying viscosities at high rates of shear. Another problem arising because of the necessary metal construction of rotational viscometers of this type is that of temperature control. All connections to the cylinders that are not adequately protected become sources of heat leaks which cause temperature gradients at the worst possible locations. A complete discussion of the various factors affecting the design and performance of cylinder apparatus can be found in the books by Barr (4) or Hatschek (17). Derivation of consistency curves for non-Newtonian liquids from cylinder viscometer data is discussed by Scott-Blair (34).

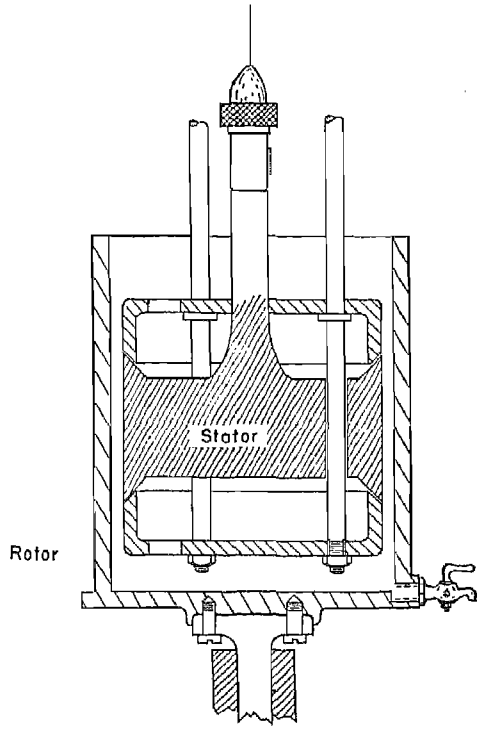


Fig. 5. Couette concentric cylinder apparatus (23).

A number of commercial viscometers are available that are based upon the cylinder principle but modified for routine industrial use. In general, these instruments are intended for relative measurements only and are not designed to eliminate end effects or to produce results of high accuracy and precision. The *MacMichael* viscometer consists of a cup containing the sample, which is rotated around an inner cylinder immersed in the sample. The inner cylinder is held stationary by the torsional force in the wire from which it is suspended and the torsion in the wire measures the viscosity of the liquid. The *Stormer* viscometer applies a constant torque to the inner cylinder, and the rate of rotation is measured. An instrument of advanced design that automatically records the torque on the stator element and that is particularly suited to materials of high consistency is available from the Precision Scientific Company (39).

While it is possible to analyze the shearing conditions most accurately with the coaxial cylinder design, it is not necessary for industrial applications to adhere to this form. Satisfactory rotational viscometers have been designed in which the rotating elements are elipsoids, disks, or other shapes; in some cases the rotating member serves

the dual purpose of stirring the sample and measuring its viscosity. A typical example is the *Brookfield* viscometer which uses a wide variety of shapes, depending upon the characteristics of the test liquid. The *Fisher Electroviscometer* is equipped with various sizes of bobbins which are held stationary within a rotating cup filled with sample. The torque exerted by the liquid upon the bobbins is measured with an ingenious electrical system, which permits sensitive readings over a wide viscosity range. In general, these instruments are for rough work only and attempts to use them for refined measurements are usually misleading.

A special class of rotational viscometer which provides many advantages in precision and sensitivity is the *oscillational* viscometer. In this type the rotating element, which may be a cylinder, sphere, disk, or other shape, is mounted in such a way that it will oscillate around its axis as a torsional pendulum. The amount of damping caused by viscous drag then measures the viscosity of the specimen. Unfortunately in gaining increased precision, the chief advantage of applicability to non-Newtonian liquids is lost since the rate of shear is no longer constant. A capillary viscometer will usually cover the effective range of oscillational viscometers with more convenience and accuracy.

FALLING-BODY VISCOMETERS

Viscometers of the falling-body type are also useful over an extremely wide viscosity range. They will satisfactorily measure viscosities of gases as well as heavy asphalts and tars. In general, they are not capable of as high precision and accuracy as the capillary or rotational viscometers, but they are excellent instruments for routine work. The driving force causing the body to fall (or rise) depends upon the difference in densities between the body and the liquid. Thus, it is necessary to determine the liquid and solid densities with considerable precision in order to interpret the rate of fall in terms of viscosity. Falling body viscometers do not allow a straightforward analysis of shearing rates and hence are usually only used for empirical studies of non-Newtonian systems. For fundamental study of non-Newtonian fluids it is generally recommended that either rotational or capillary tube instruments be used.

It is theoretically possible to use falling spheres for absolute measurements by applying Stokes' law; however, it is difficult to obtain precision spheres of a size that is well suited to this application. Also, the effects of the walls of the confining vessel and of turbulent flow are difficult to evaluate. The absolute method is therefore seldom used. The rate of fall of a sphere can be represented by the formula:

$$\eta = K(d_s - d_l)t \tag{14}$$

where K = a proportionality constant; d_s = the density of the sphere; d_l = the density of the liquid; and t = the time of fall through a given distance. It is therefore possible to calibrate a falling-ball viscometer by a step-up procedure. It is preferable, however, to calibrate liquids in the desired range by means of an absolute viscometer such as the Couette type and to use these liquids for standardizing the falling-ball viscometer. Higher precision can be attained if the sphere rolls down a wall of the container instead of falling freely through the liquid. The theory for this case is complicated but equation (14) applies satisfactorily over short ranges. A very simple falling-sphere viscometer is in common use for specification testing of soluble nitrocellulose (A.S.T.M. D-301–33), and cellulose acetate (A.S.T.M. D871–48). It consists of a cylinder exactly 1 in. in diameter with two marks 10 cm. apart and a steel

ball of carefully specified dimensions. An aluminum funnel placed in the mouth of the tube assures that the ball is dropped centrally. In using the apparatus the cylinder is filled with the liquid and brought to temperature. The ball is then dropped through the funnel into the liquid, and the time required for it to fall between the marks is measured. A more precise instrument using a rolling ball is the *Höppler* viscometer (18). Its construction and method of operation are evident from Figure 6. A series of balls are provided which cover the range from 0.01 to 25,000 poise. Another version of the falling-ball viscometer, also by Höppler, is useful in the viscosity range above one kilopoise. Instruments intended for use in this range are usually called *consistometers*

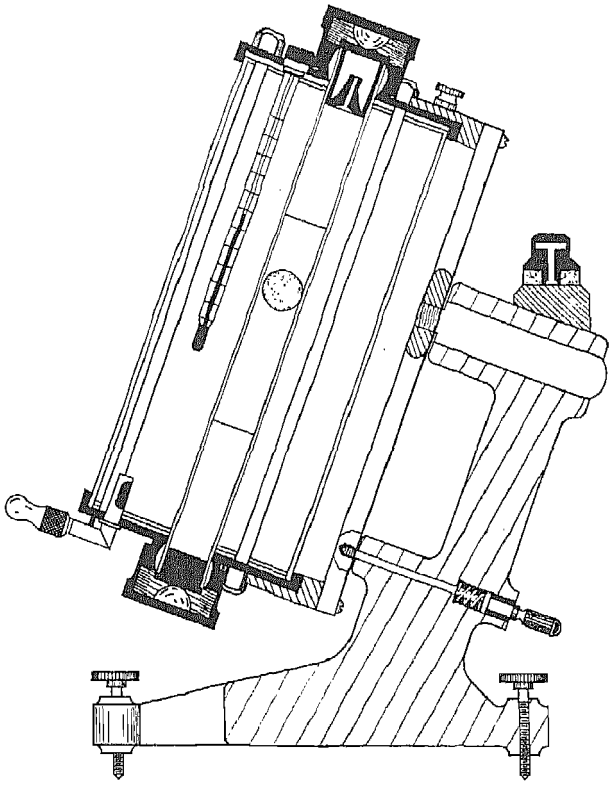


Fig. 6. Höppler viscometer (23).

(2). A falling-ball instrument especially for work at high pressures was designed by Weber (2). In his apparatus, the passage of the ball by the fiducial marks is observed by means of induction coils surrounding the sample tube. Falling cylinders, cones, and needles are convenient in many applications; for example Bridgman for his famous viscosity measurements at high pressures used a special falling-cylinder viscometer (7). Penetrometers, used for determining the consistency of materials of high viscosity such as asphalts, waxes, greases and others, are also examples in this class. The term "consistency" includes not only viscous, but also elastic and plastic and other non-Newtonian elements. The observations made by means of the penetrometer nevertheless can have a simple significance in connection with measurement of viscosity when the substance under test exhibits essentially Newtonian flow properties. This is true in the case of many steam-refined asphalts, typically those of Californian origin,

and the light-colored asphalts from Miri, Borneo. For asphalts of this kind a relation has been established (33) between the penetration observed in decimillimeters, and absolute viscosity, y, in poises:

$$y = \frac{5.13^9}{\text{pen}^{1.93}} \tag{15}$$

This formula is said to apply to penetrations between 5 and 200.

Falling needles have been used for accurate work at high pressures inside sealed systems (25,36). Needles that were specially designed to avoid irregular or fluttering fall were allowed to fall through the liquid in a capillary tube. When the passage of the needles could not be directly observed, electromagnetic methods were employed.

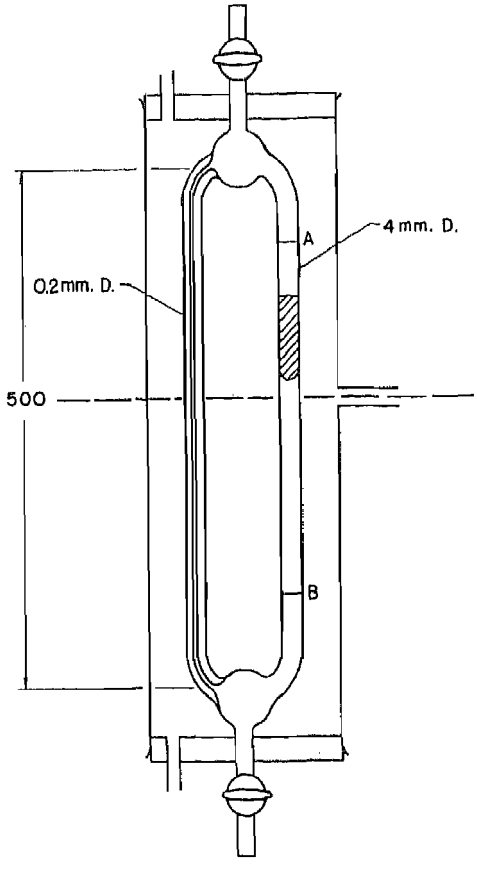


Fig. 7. Rankine gas viscometer (31a).

A special case of the falling-body principle is that of the rising bubble. A glass tube of standardized dimensions is filled to a mark with liquid at the test temperature, and the tube is closed with a definite amount of air above the mark. When the tube is at the desired temperature it is inverted and the rate of rise of the bubble is observed. The absolute rate of rise can be calibrated in terms of viscosity, but it is more common to use a set of standards prepared in similar tubes, bracketing the sample. This method is extensively used in the paint and varnish industry (13).

MISCELLANEOUS VISCOMETERS

Gas Viscometers. The viscometry of gases is normally carried out in a capillary instrument such as that of Rankine shown in Figure 7. The tube is sealed off at any desired gas pressure and the time required for a mercury pellet to fall between marks in the larger tube is measured. The details of operation and the various factors influencing precision and accuracy are discussed by Barr (4) and by Rankine (31a).

Viscometers Involving Approaching or Receding Surfaces. When two plates or surfaces are brought together or pulled apart with a layer of fluid contained between them, the rate of separation or approach for a given applied force is related to the viscosity. Michell (44) used this principle in an apparatus consisting of a steel sphere fitting into a spherical cup with clearance of about 0.01 mm. adjusted by means of three small pegs projecting radially inwards from the cup. The sphere is placed in the cup and the separating space is filled with oil. The cup is inverted and the time for the sphere to fall away is proportional to the viscosity of the oil in poises. The main ad-

vantage of the Michell instrument is the small amount of sample required. A recent model described by Campbell and Darn (9) can be used with one drop of liquid over a wide range of viscosities. Results are usually only accurate to within about 1%.

The same principle is used in tackmeters for the printing ink industry which act as a mechanical finger (14).

Ultrasonic and Vibrating-Disk Instruments. An interesting viscometer that utilized a small disk vibrating in its own plane in the fluid at a rate of 800 cycles per second was described by Woodward (43). The amplitude of the vibration, measured by means of piezoelectricity generated in barium titanate blocks, provided a direct indication of the product of viscosity and density. The instrument could be used for the range 0.01 to 100,000 centipoise with an accuracy of about 5%. The principal advantages lay in the possibilities for continuous recording of viscosity changes in commercial installations. A similar device, the Ultra-viscoson, using ultrasonic frequencies, is available commercially (32). These instruments are not suitable for use with non-Newtonian liquids.

Instruments Providing High Rates of Shear. A band viscometer, devised by Wachholtz and Asbeck (40), provides high rates of shear as well as simplicity of construction and operation. A thin band is drawn through a narrow gap between two carefully lapped blocks. The blocks have a small reservoir of liquid at the top and the gap remains full of liquid during the test. The tape is self-centering and its action corresponds to the ideal situation in which two planes separated by a given thickness of oil are moved relative to each other. The velocity is measured for varying driving forces. The same apparatus has also been used by Hull (19), who found it well suited for materials having viscosities from 5 to 1000 poises.

Another high-shear-rate viscometer combining the centering principle of the band viscometer with the construction of a concentric cylinder viscometer was devised by Asbeck, Laiderman, and Van Loo (1a). This instrument could attain shear rates above 20,000 sec.$^{-1}$ without excessive heating effects, and was designed especially for measurement of viscosities of paint under conditions comparable to brushing.

Instruments for Measurements of Elastic Properties and Non-Newtonian Behavior. This topic is covered under *Rheology* and will not be discussed here (see especially references (3,21,28,30) of *Rheology*, Vol. **11**, pp. 729–30). Two noteworthy instrumental developments in recent years include the use of torsionally oscillating crystals (22) and the Weissenberg Rheo-Goniometer (41). Further information can be found in other reviews (3,29) or symposiums.

Bibliography

(1) Andrade, E. N. D. C., *Nature*, **125**, 309, 582 (1930).

(1a) Asbeck, W. K., Laiderman, D. D., and Van Loo, M., *J. Colloid Sci.*, **7**, 306–15 (1952).

(2) *Arch. Tech. Messen*, **9122-7**, T-137 (1900).

(3) *Arch. Tech. Messen*, **9122**, 6, 7 (1950).

(4) Barr, G., *A Monograph of Viscometry*, Oxford Univ. Press, London, 1931.

(5) Barr, G., *J. Phys. Soc. (London)*, **58**, 575–85 (1946).

(6) Bashforth, F., and Adams, J. C., *An Attempt to Test the Theory of Capillary Action*, Cambridge Press, 1883.

(7) Bridgman, P. W., *Proc. Natl. Acad. Am.*, **11**, 603 (1925).

(8) Bridgman, P. W., *Proc. Am. Acad. Arts Sci.*, **61**, 57 (1926); **62**, 187 (1927).

(9) Campbell, W. E., and Darn, P. D., Paper presented at the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, March 1–15, 1954.

(10) Clark, O. H., and Deutsch, M. L., *J. Applied Phys.*, **21**, 713–15 (1950).
(11) Dean, E. W., and Davis, G. H. B., *Ind. Eng. Chem.*, **32**, 102 (1940).
(12) Ford, T. F., and Arabian, K. G., *Proc. Am. Soc. Testing Materials*, **40**, 1174–81 (1940).
(13) Gardner, H. A., *Physical and Chemical Examination of Paints, Varnishes, Lacquers and Colors*, 10th ed., Gardner Lab., Bethesda, Md., 1946.
(14) Green, H., *Industrial Rheology and Rheological Structures*, Wiley, N.Y., 1949, pp. 114–21.
(15) Griffin, R. C., *Technical Methods of Analysis*, McGraw-Hill, N.Y., 1927.
(16) Gurney, L. E., *Phys. Rev.*, **26**, 98–120 (1908).
(17) Hatschek, E., *The Viscosity of Liquids*, Bell and Sons, London, 1928.
(18) Höppler, F., *Z. tech. Phys.*, **14**, 165 (1933).
(19) Hull, H. S., *J. Colloid Sci.*, **7**, 316–22 (1952).
(20) Lillie, H. R., *J. Am. Ceram. Soc.*, **12**, 505–15 (1929); *Phys. Rev.*, **36**, 347–62 (1930).
(21) Lindsley, C. H., and Fischer, E. K., *J. Applied Phys.*, **18**, 988–96 (1947).
(22) Mason, W. P., *J. Colloid Sci.*, **3**, 147 (1948).
(23) McGoury, T. E., and Mark, H., in Weissberger, *Physical Methods of Organic Chemistry*, 2nd ed., Interscience, N.Y., 1949, Vol. I, pt. 1.
(24) Mooney, M., and Ewart, R. H., *Physics*, **5**, 350 (1934).
(25) Nederbragt, G. W., and Boelhouwer, J. W. M., *Physica*, **13**, 305 (1947).
(26) Newton, I., *Principia*, Lib. II.
(27) Örne, N., *Proceedings of the Second International Congress of Rheology*, Academic Press, N.Y., 1954, pp. 316–19.
(28) Philipoff, W., *Viskosität der Kolloide*, Steinkopff, Dresden, 1942.
(29) *Proceedings of the Second International Congress of Rheology*, Academic Press, N.Y., 1954.
(30) *Proc. Am. Soc. Testing Materials*, **49**, 338 (1949).
(31) Rabinowitsch, B., *Z. physik. Chem.*, **A145**, 1–26 (1929).
(31a) Rankine, A. O., *J. Sci. Instruments*, **1**, 105 (1924).
(32) Roth, W., and Rich, S. R., *J. Applied Phys.*, **24**, 94–150 (1953).
(33) Saal, R. N. J., and Koens, G., *J. Inst. Petroleum Technol.*, **19**, 176 (1933).
(34) Scott-Blair, G. W., *A Survey of General and Applied Rheology*, 2nd ed., Pitman, London, 1949.
(35) Searle, G. F. C., *Proc. Camb. Phil. Soc.*, **16**, 600–6 (1912).
(36) Seeder, R., *Physica*, **6**, 45 (1940).
(37) Swindells, J. F., Coe, J. F., Jr., and Godfrey, T. B., *J. Research Natl. Bur. Standards*, **48**, 1–31 (1952).
(38) Swindells, J. R., Hardy, R. C., and Cottington, R. L., *J. Research Natl. Bur. Standards*, **52**, 105–15 (1954).
(39) Traxler, R. N., Romberg, J. W., and Schweyer, H. E., *Ind. Eng. Chem., Anal. Ed.*, **14**, 340 (1942).
(40) Wachholtz, F., and Asbeck, W. K., *Kolloid Z.*, **93**, 280–97 (1940).
(41) Weissenberg, K., *Proceedings of the International Congress on Rheology*, N. Holland Pub. Co., Amsterdam, 1949, Pt. 2, p. 114.
(42) Willihnganz, E. A., McCluer, W. B., Fenske, M. R., and McGrew, R. V., *Ind. Eng. Chem., Anal. Ed.*, **6**, 231–34 (1943).
(43) Woodward, J. G., *J. Colloid Sci.*, **6**, 481–91 (1951).
(44) Brit. Pat. 117,234 (1917), R. Michell.

F. H. STROSS AND P. E. PORTER

VISCOSE. See *Rayon.*

VISCOSITY. See *Rheology; Viscometry.*

VITAL STAINS. See *Stains, microscopical (biological).*

VITAMINS

p-Aminobenzoic acid.....Vol. 2, p. 472
Ascorbic acid.....Vol. 2, p. 150
Biotin.....Vol. 2, p. 519
Choline.....Vol. 3, p. 919
Folic acid.....Vol. 6, p. 778
Inositol.....Vol. 7, p. 877
Nicotinic acid and nicotinamide.....Vol. 9, p. 305
Pantothenic acid.....Vol. 9, p. 805
Pyridoxine, pyridoxal, and pyridoxamine.....Vol. 11, p. 293
Riboflavin.....Vol. 11, p. 749
Thiamine.....Vol. 14, p. 38
Vitamin A.....Vol. 14, p. 791
Provitamins A.....Vol. 14, p. 801
Vitamin B_{12}.....Vol. 14, p. 813
Vitamin D.....Vol. 14, p. 828
Provitamins D.....Vol. 14, p. 829
Vitamin E (tocopherols).....Vol. 14, p. 849
Vitamin K.....Vol. 14, p. 858

SURVEY

Vitamins may be defined (16) as "organic compounds which are required for the normal growth and maintenance of life of animals, including man, who, as a rule, are unable to synthesize these compounds by anabolic processes that are independent of the environment other than air, and which compounds are effective in small amounts, do not furnish energy, and are not utilized as building units for the structure of the organism but are essential for the transformation of energy and for the regulation of the metabolism of structural units."

Provitamins are organic compounds which can be converted into specific vitamins within the organism. This transformation may occur as the result of the body's ability to carry out this function or as the result of an outside force. There are only two types of known provitamins, namely, provitamins A and provitamins D. Certain carotenoids, especially the carotenes, are provitamins A and are converted into vitamins A (see p. 810) through a special enzyme system. The provitamins D are transported to the skin, where they are converted into vitamins D by means of ultraviolet light such as supplied by the sun (see p. 838).

Nomenclature. The term "vitamine" (from Latin *vita*, life, and *amine*) was first used by Funk (6) in 1912 to describe the so-called accessory factors because these compounds were essential to life and because Funk believed the antiberiberi factor to be an amine. Osborne and Mendel (15) and McCollum and Davis (11) in 1915 distinguished two types of factors by their difference in solubility and called them fat-soluble A (shown to cure eye disease) and water-soluble B (prevented beriberi in pigeons). In 1920 Drummond (4) proposed the names vitamin A for the eye factor, vitamin B for the antiberiberi factor, and vitamin C for the antiscurvy factor. As other vitamins were discovered, they were assigned consecutive letters of the alphabet.

The apparent inconsistency in the nomenclature of the vitamins can be understood from a study of their historical development. The original vitamin B, for instance, was subsequently found to be a mixture of compounds which have been arbitrarily designated vitamin B_1, B_2, etc. On the other hand, the fact that a dietary deficiency of a single vitamin might be associated with a number of diverse symptoms could not be immediately recognized. This led to a multiplicity of names for a single entity. With the chemical identification of the vitamins, they were assigned names in accordance with the class to which they belonged. Table I (18) summarizes the present knowledge of the nomenclature, action, and chemistry of the vitamins.

TABLE I. Vitamin Nomenclature.[a,b,c]

Vitamin group	Characterization	Common name	Chemical and other names
Vitamin A group	Antixerophthalmic factor, necessary for prevention of night blindness, for proper reproduction and egg production	Vitamin A[a]	Axerophthol; all-*trans*-3,7-dimethyl-9-(2,6,6-trimethyl-1-cyclohexen-1-yl)-2,4,6,8-nonatetraen-1-ol
Vitamin A_1			
Vitamin A_2			Dehydrovitamin A
Neovitamin A			Cis isomers of vitamin A
etc.			
α-Carotene	The carotenes and cryptoxanthin are converted to vitamin A by enzymes found, for example, in the intestinal mucosa	Carotene[a] (mixt.)	Provitamins A
β-Carotene			
γ-Carotene			
Cryptoxanthin			
etc.			
Vitamin B	Original name given to the crude preparations that relieved beriberi; later found to contain many factors		Water-soluble B
Vitamin B complex	Factors isolated from yeast, liver, and other sources of the original "water-soluble B"; includes all the vitamins listed from this point up to vitamin C	The B vitamins	
Vitamin B_1	Antiberiberi factor; a component of cocarboxylase	Thiamine[a,b]	Aneurin(e); antineuritic factor; vitamin F; 3-(4-amino-2-methyl-5-pyrimidinylmethyl)-5-(2-hydroxyethyl)-4-methylthiazolium chloride
Vitamin B_2	A component of Warburg's "yellow enzyme"; essential for cellular oxidation and reduction	Riboflavin,[a] riboflavine[b]	Vitamin G; lactoflavin; ovoflavin; hepatoflavin; 6,7-dimethyl-9-(D-1-ribityl)isoalloxazine
(Vitamin B_3)	Necessary for the growth of pigeons; possibly the same as pantothenic acid		
(Vitamin B_4)	Prevents muscular weakness in rats and chicks; probably a mixture of riboflavin and pyridoxine, but also described as a mixture of arginine and glycine		
(Vitamin B_5)	Necessary for growth of pigeons; probably nicotinic acid		

Vitamin B_6 group	Prevents a specific dermatitis in young rats and in man, convulsions in infants; component of amino acid decarboxylation and transamination coenzymes	Vitamin B_6	Pyridoxine[b]; eluate factor; rat acrodynia factor; adermin(e), vitamin Y
Pyridoxine[a]		Pyridoxine[a]	Pyridoxol[b]; 2-methyl-3-hydroxy-4,5-bis(hydroxymethyl)pyridine
Pyridoxal[b]			2-Methyl-3-hydroxy-5(hydroxymethyl)isonicotinaldehyde
Pyridoxamine[b]			2-Methyl-3-hydroxy-4-aminomethyl-5-hydroxymethylpyridine
(Vitamin B_7)	A factor in rice polishings that prevents digestive disturbances in pigeons		Vitamin I; rice polish factor
(Vitamin B_8)	Adenylic acid, a participant in phosphate transfer in many types of organisms; not usually classified as a vitamin; see Vol. 9, p. 509		
(Vitamin B_9)	Number unused because nine B vitamins were recognized when vitamins B_{10} and B_{11} were announced		
(Vitamin B_{10})	Chick feathering factor; probably a mixture of folic acid and vitamin B_{12}		
(Vitamin B_{11})	Chick growth factor; probably a mixture of folic acid and vitamin B_{12}		
Vitamin B_{12} group	Antipernicious anemia principle		
Vitamin B_{12}		Vitamin B_{12}	Cobalamins[a,b]
		Cyanocobalamin[a,b]	Extrinsic factor; erythrocyte maturation factor; probably animal protein factor
Vitamin B_{12a}	Vitamin B_{12a}, vitamin B_{12b}, and vitamin B_{12d} reported to be identical		Hydroxocobalamin[b]
Vitamin B_{12b}			
Vitamin B_{12c}			Nitrocobalamin; nitritocobalamin[b]
(Vitamin B_{12d})			
(Vitamin B_{13})	An uncharacterized factor, discovered in distillers' dried solubles, that promotes growth of rats, pigs, chicks, etc.		
(Vitamin B_{14})	Originally thought to be a metabolite of xanthopterin (related to folic acid); data not confirmed		

(*Continued*)

TABLE I. Vitamin Nomenclature (*Continued*).

Vitamin group	Characterization	Common name	Chemical and other names
(Vitamin B_{15})	Reported to facilitate oxygen uptake in the presence of anoxic or histiotoxic anoxia in rabbits; not confirmed		Pangamic acid
(Vitamin B_c)	Chick factor; identical with folic acid		
(Vitamin B_p)	Antiperosis factor for chicks, considered replaceable by manganese and choline		
(Vitamin B_t)	Growth factor for meal worm (*Tenebrio*); identified as carnitine		
(Vitamin B_w)	Name applied to biotin		
(Vitamin B_x)	Name applied to either pantothenic or *p*-aminobenzoic acid		
Nicotinamide[a,b]	Prevents pellagra; a component of hydrogen-transferring coenzyme I and II	Niacinamide[a]	Nicotinic acid amide; PP factor (pellagra-preventing factor); antiblacktongue factor; 3-pyridinecarboxylic acid amide
Nicotinic acid[a,b]	Converted to nicotinamide in the body	Niacin[a]	3-Pyridinecarboxylic acid
Pantothenic acid[a,b]	Prevents dermatitis in chicks and gray hair in rats; a component of acetyl-transferring coenzyme A	Pantothenic acid[a,b]	Filtrate factor; chick antidermatitis factor; chick antipellagra factor; liver factor II; antiachromotrichia factor (anti-gray-hair factor); D(+)-*N*-(2,4-dihydroxy-3,3-dimethylbutyryl)-β-alanine
Biotin[b]	Cures alopecia (baldness) and "spectacle eye" in rats fed a biotin-deficient diet supplemented by raw egg whites; prevents perosis in chicks	Biotin[b]	Anti-egg-white injury factor; vitamin H or B_w; coenzyme R; bios II or IIb; factor S; factor W; factor X; *cis*-tetrahydro-2-oxothieno[3,4]imidazoline-4-valeric acid
Biocytin	Source of biotin for certain microorganisms		N^6-Biotinyl-L-lysine
Choline[a,b]	Required for transmethylation	Choline[a,b]	Bilineurine; 2-(hydroxyethyl)trimethylammonium hydroxide
Inositol[a]	Prevents baldness and "spectacle eye" in mice and other animals	Inositol[a], meso-inositol[b]	*meso*-Inositol; myoinositol; *i*-inositol; inosite; bios I; mouse antialopecia factor; muscle sugar; hexahydroxycyclohexane

p-Aminobenzoic acid[a,b]	Prevents gray hair in black rats and promotes growth in chicks; component of folacin	Para-aminobenzoic acid[a]	PABA
Folic acid group	Involved in transfer and metabolism of "single-carbon" fragment; prevents macrocytic (megaloblastic) anemia	Folic acids[b]	Generic term for a group of pteroylglutamic acids formerly known as vitamin M, vitamin B_c, factor U, *Lactobacillus casei* factor, Norite eluate factor, factor R, etc.
Pteroylglutamic acid[a]		Folic acid[a]	Pteroylmonoglutamic acid[b]; folacin; PGA; *N*-{*p*-[(2-amino-4-hydroxy-6-pteridylmethyl)amino]benzoyl}glutamic acid
Pteroyltriglutamic acid		Teropterin	Pteroyldi-γ-glutamylglutamic acid
Pteroylheptaglutamic acid			Vitamin B_c conjugate; pteroylglutamic acid conjugate; pteroylhexaglutamylglutamic acid
Pteroic acid[b]		Pteroic acid[b]	*p*-[(2-Amino-4-hydroxy-6-pteridylmethyl)-amino]benzoic acid
10-Formylpteroic acid		Rhizopterin	
10-Formylpteroylglutamic acid			
Folinic acids	Growth factor for *Leuconostoc citrovorum*		Citrovorum factor; CF; tetrahydropteroylglutamic acids
Leucovorin, etc.		Folinic acid-SF	5-Formyl-5,6,7,8-tetrahydropteroylglutamic acid
Lipoic acid group	Pyruvate and α-ketoglutarate oxidation factor; acetate formation factor		Protogens
α-Lipoic acid		α-Lipoic acid	Thioctic acid; 6(or 6,8)-thioctic acid; protogen A; 6,8-epidithiooctanoic acid; 1,2-dithiolane-3-valeric acid
β-Lipoic acid		β-Lipoic acid	Thioctic acid *S*-oxide; protogen B
γ-Lipoic acid		γ-Lipoic acid	Dihydrothioctic acid; 6,8-dimercaptooctanoic acid
Vitamin C	Antiscorbutic factor	Ascorbic acid[a,b]	L-Xyloascorbic acid; antiscorbutic factor; cevitamic acid; L-*threo*-2,3,4,5,6-pentahydroxy-2-hexeno-γ-lactone
(Vitamin C_2)	Vitamin J		

(*Continued*)

TABLE I. Vitamin Nomenclature[a,b,c] (*Concluded*).

Vitamin group	Characterization	Common name	Chemical and other names
Vitamin D group	Antirachitic vitamin	Vitamin D	Antirachitic factor
Vitamin D_2	Plant-type vitamin D, active in man and four-footed animals	Calciferol[a]	Ergocalciferol[b]; activated or irradiated ergosterol; 9,10-seco-5,7,10(19),22-ergostatetraen-3β-ol
Vitamin D_3	Animal-type vitamin D, active in man and all species of animals, including chicks	Activated (or irradiated)7-dehydrocholesterol[a]	Cholecalciferol[b]; 9,10-seco-5,7,10(19)-cholestatrien-3β-ol
Vitamin E group	Prevents sterility, blood and vascular system disorders, central nervous system degeneration, and muscular dystrophy in experimental animals	Vitamin E	Antisterility factor; the tocopherols
α-Tocopherol[a,b]			2,5,7,8-Tetramethyl-2-(4,8,12-trimethyltridecyl)-6-chromanol; 5,7,8-trimethyltocol
β-Tocopherol[a,b]			5,8-Dimethyltocol
γ-Tocopherol[a,b]			7,8-Dimethyltocol
δ-Tocopherol[a]			8-Methyltocol
(Vitamin F)	Obsolete designation for essential fatty acids; also an obsolete name for vitamin B_1		
(Vitamin G)	Obsolete name for riboflavin		
(Vitamin H)	Obsolete name for biotin		
(Vitamin I)	Vitamin B_7		
(Vitamin J)	Postulated as antipneumonia principle		Vitamin C_2
Vitamin K group	Blood-clotting factor	Vitamin K	Koagulations Vitamin (German name); antihemorrhagic factor
Vitamin K_1		Phylloquinone[b]	Phytonadione[a]; 2-methyl-3-phytyl-1,4-naphthoquinone
Vitamin K_2		Farnoquinone[b]	2-Methyl-3-difarnesyl-1,4-naphthoquinone
Menadione[a]		Menadione[b]	Vitamin K_3; 2-methyl-1,4-naphthoquinone
etc.			

(Vitamins L_1 and L_2)	Postulated as necessary for maturation of lactation tissue	
(Vitamin M)	Obsolete name for folic acid; factor for prevention of anemia and leucopenia in monkeys	
(Vitamin P group)	A group of factors that decrease capillary fragility; vitamin character uncertain	Citrin; permeability factors including the bioflavonoids, as certain flavanone glycosides, e. g., hesperidin, rutin[a] (see Vol. 3, p. 603)
(Vitamin R)	Promotes bacterial growth; probably one of the folic acid group	
(Vitamin S)	Promotes bacterial growth; probably biotin; also applied to streptogenin, a chick growth factor	
(Vitamin T)	Reported to improve protein assimilation in rats and produce gigantism in insects	Termite factors
(Vitamin U)	Promotes bacterial growth; probably one of the folic acid group; term "vitamin U" also used for anti-ulcer factor in cabbage juice	
(Vitamin V)	Promotes bacterial growth; probably diphosphopyridine nucleotide, the nicotinamide coenzyme	
(Vitamin W)	Promotes bacterial growth; probably biotin	
(Vitamin X)	Promotes bacterial growth; probably biotin	
(Vitamin Y)	Probably identical with pyridoxine	

Adapted from ref. (18).
[a] Official names of U.S.P. XV, N.F. X, and N.N.R.
[b] Names approved by I.U.P.A.C. (see *J. Chem. Soc.*, **1951**, 3526; *Bull. soc. chim. biol.*, **33**, 1663 (1951); *Chem. Eng. News*, **30**, 104 (1952); **33**, 2433 (1955).
[c] Names no longer used are in parentheses.

ISOLATION, SYNTHESIS, AND MANUFACTURE

For the occurrence of vitamins and vitamin content of various foods, see the articles on the specific vitamins and such articles as *Cereals*, Vol. **3**, pp. 601, 625, 632; *Dairy products*, Vol. **4**, pp. 780, 833; *Fish-liver oils*, Vol. **6**, p. 570; *Food and food processing*, Vol. **6**, pp. 788, 812; *Meat*, Vol. **8**, p. 826; *Molasses*, Vol. **9**, p. 169; *Nuts*, Vol. **9**, p. 555; *Yeasts*.

All the vitamins which have been isolated have been synthesized with the exception of vitamin D and the vitamins of the B_{12} group, the structural formulas of which are not known. Most of the vitamins handled commercially are produced by synthesis. These include most of the B vitamins, notably thiamine, riboflavin, nicotinic acid, pantothenic acid, pyridoxine, folic acid, *p*-aminobenzoic acid, and biotin.

TABLE II. Commercial Production of Vitamins in the U.S., 1938–53.

(In thousands of pounds.)

	Vitamin A	Thiamine (B_1)	Riboflavin (B_2)	Pyridoxine (B_6)	Vitamin B_{12}	Vitamin D_2[a]	Vitamin D_3[a]
1938	—	—	—	—	—	—	—
1939	—	—	—	—	—	—	—
1940	—	—	—	—	—	—	—
1941	—	—	5	—	—	0.04	—
1942	—	—	16	—	—	0.33	—
1943	—	—	72	—	—	0.79	—
1944	9	153	85	4.2	—	1.87	—
1945	—	170	69	2.7	—	1.34	—
1946	—	185	45	10.3	—	1.84	—
1947	—	166	—	12.9	—	0.94	—
1948	—	190	130	10.9	—	0.70	—
1949	79	188	160	10.0	—	1.16	1.23
1950	95	237	199	18	—	1.60	1.00
1951	234	268	245	22	0.084	1.40	1.30
1952	397	224	236	14	0.094	1.45	1.25
1953	113	277	266	18	0.387	1.43	1.34

	Niacin and niacinamide	Vitamin K	All other cyclics	Ascorbic acid (C)	Pantothenic acid	All other acyclics	Total[b]
1938	—	—	—	8.7	—	—	(8.7)
1939	—	—	—	15.7	—	—	(15.7)
1940	(22.3)	—	—	33.4	—	—	(55.7)
1941	143	—	—	92	—	—	(240)
1942	290	—	—	260	—	—	(566)
1943	(543)	(0.3)	—	763	(14)	—	(1,393)
1944	940	0.4	41	1,177	32.7	—	(2,443)
1945	958	0.9	64	1,307	(58)	—	(2,630)
1946	1,001	0.4	146	728	(98)	—	(2,215)
1947	1,070	1.1	282	657	(89)	—	(2,280)
1948	1,134	—	55	956	(90)	—	(2,566)
1949	1,238	0.8	60	968	113	—	(2,819)
1950	1,448	—	73	1,228	155	—	(3,456)
1951	1,596	1.9	181	1,552	240	—	(4,343)
1952	2,122	1.2	276	1,393	(261)	—	(4,927)
1953	1,893	1.0	131	1,672	286	20	(4,686)

[a] Vitamin D_2 and vitamin D_3 production data converted from billions of U.S.P. units to pounds, using the factor 18.14 billion U.S.P. units per pound 100% crystalline vitamin D_2.

[b] Sum of individual production data of vitamins.

Inositol is isolated from natural sources, for example, corn. Vitamin B_{12} is produced by microbial fermentation. Commercially, vitamin B_{12} concentrates are manufactured by primary fermentation or from fermentation residues of certain antibiotics such as chlortetracycline and streptomycin. Fermentation is also used to produce riboflavin economically. The broth is dried and the dry residue sold on the basis of its riboflavin content. These and other fermentation by-products, such as the dried "distillers' solubles" are highly valued as a source of unidentified vitamin factors. Vitamins A and E are still produced by isolation as well as by synthesis. In the case of vitamin K, 2-methyl-1,4-naphthoquinone (menadione), a synthetic compound with vitamin K activity, is manufactured for commercial use. Table II summarizes the data for the commercial production of vitamins in the U.S. from 1938 through 1953 as provided by the U.S. Tariff Commission.

BIOLOGICAL ACTION

The specificity of the vitamins may be differentiated into two types: namely, compound specificity and species specificity. By *compound specificity* is meant the qualitative and quantitative differences in physiological behavior of various compounds in the same kind of animal. Specificity studies of the vitamins, as with pharmaceutical compounds, have made it possible to ascertain whether or not the vitamin activity of a particular compound is due to the structure of the entire compound or to a special part of the molecule. *Species specificity* is defined as the difference in physiological response of different animals to one or more compounds. Species vary considerably in their needs for the different vitamins, certain species thriving in the absence of vitamins which are essential for others.

The knowledge of the mechanism of vitamin action in the organism is based upon experimental data and must be qualified as to the exact conditions of the experiments. A slight variation in experimental conditions may give rise to completely different results which lead to diverse interpretations. As a result, a tremendous amount of

TABLE III. Toxicity of Vitamins.

Vitamin	LD_{50}	Route	Animal
Thiamine	125 mg./kg.	Intravenous	Mice
	250 mg./kg.	Intravenous	Rats
	300 mg./kg.	Intravenous	Rabbits
	350 mg./kg.	Intravenous	Dogs
Nicotinic acid	4–5 g./kg.	Subcutaneous	Mice, rats
	5–7 g./kg.	Oral	Mice, rats
Riboflavin	560 mg./kg.	Intraperitoneal	Rats
Pyridoxine.HCl	3.7 g./kg.	Subcutaneous	Rats
	5.5 g./kg.	Oral	Rats
Pantothenic acid	2.7 g./kg.	Subcutaneous	Mice
	3.4 g./kg.	Subcutaneous	Rats
	2 g./kg.	Intravenous	Rabbits
Pteroylglutamic acid	600 mg./kg.	Intravenous	Mice
	500 mg./kg.	Intravenous	Rats
	410 mg./kg.	Intravenous	Rabbits
	120 mg./kg.	Intravenous	Guinea pigs
Choline	320 mg./kg.	Intraperitoneal	Mice
	6.7 g./kg.	Oral	Rats
Menadione	0.5 g./kg.	Oral	Mice

Table IV. National Research Council Recommended Daily Dietary Allowances.[a,b]

(Allowances are considered to apply to persons normally vigorous and living in temperate climate.)

Group	Age, yr.	Weight, kg. (lb.)	Height, cm. (in.)	Calories	Protein, g.	Calcium, g.	Iron, mg.	Vitamin A, I.U.	Thiamine, mg.	Riboflavin, mg.	Niacin, mg.	Ascorbic acid, mg.	Vitamin D, I.U.
Men	25	65 (143)	170 (67)	3,200	65	0.8	12	5,000	1.6	1.6	16	75	—
	45	65 (143)	170 (67)	2,900	65	0.8	12	5,000	1.5	1.6	15	75	—
	65	65 (143)	170 (67)	2,600	65	0.8	12	5,000	1.3	1.6	13	75	—
Women	25	55 (121)	157 (62)	2,300	55	0.8	12	5,000	1.2	1.4	12	70	—
	45	55 (121)	157 (62)	2,100	55	0.8	12	5,000	1.1	1.4	11	70	—
	65	55 (121)	157 (62)	1,800	55	0.8	12	5,000	1.0	1.4	10	70	—
Pregnant (3rd trimester)				Add 400	80	1.5	15	6,000	1.5	2.0	15	100	400
Lactating (850 ml. daily)				Add 1,000	100	2.0	15	8,000	1.5	2.5	15	150	400
Infants	0 to $^1/_{12}$												
	$^1/_{12}$ to $^3/_{12}$	6 (13)	60 (24)	kg. × 120	kg. × 3.5	0.6	6	1,500	0.3	0.4	3	30	400
	$^3/_{12}$ to $^9/_{12}$	9 (20)	70 (28)	kg. × 110	kg. × 3.5	0.8	6	1,500	0.4	0.7	4	30	400
	$^{10}/_{12}$ to 1	10 (22)	75 (30)	kg. × 100	kg. × 3.5	1.0	6	1,500	0.5	0.9	5	30	400
Children	1–3	12 (27)	87 (34)	1,200	40	1.0	7	2,000	0.6	1.0	6	35	400
	4–6	18 (40)	109 (43)	1,600	50	1.0	8	2,500	0.8	1.2	8	50	400
	7–9	27 (59)	129 (51)	2,000	60	1.0	10	3,500	1.0	1.5	10	60	400
Boys	10–12	35 (78)	144 (57)	2,500	70	1.2	12	4,500	1.3	1.8	13	75	400
	13–15	49 (108)	163 (64)	3,200	85	1.4	15	5,000	1.6	2.1	16	90	400
	16–20	63 (139)	175 (69)	3,800	100	1.4	15	5,000	1.9	2.5	19	100	400
Girls	10–12	36 (79)	144 (57)	2,300	70	1.2	12	4,500	1.2	1.8	12	75	400
	13–15	49 (108)	160 (63)	2,500	80	1.3	15	5,000	1.3	2.0	13	80	400
	16–20	54 (120)	162 (64)	2,400	75	1.3	15	5,000	1.2	1.9	12	80	400

[a] Revised 1953.

[b] Other nutrients discussed in the publication include: carbohydrate and fat, water, sodium, potassium, chlorine, phosphorus, copper, iodine, fluorine, trace elements, vitamin B_6 group, vitamin B_{12}, folacin (folic acid), pantothenic acid, biotin, and vitamin K.

research is necessary to establish the true physiological actions of the vitamins, and in most cases a final understanding has not been reached.

Substantial advances in this respect have been made already, however. Many vitamins of the B complex have been recognized as distinct moieties within coenzymes of known structure (see Vol. **5**, p. 741). These coenzymes are involved in such diverse living activities as carbohydrate, protein, and fat metabolism and the physiology of vision.

Molitor and Emerson (12) have reviewed comprehensively the pharmacology of the vitamins, including the effect of vitamins on normal animals and on animals affected by diseases other than avitaminosis. In general, vitamins have a very low order of toxicity (see Table III).

ASSAYS AND STANDARDS

The measurement of vitamin potency is important for feed and food control as well as therapeutic purity. Three main types of assays are employed: chemical or physicochemical, biological, and microbiological. Accepted methods for various purposes have been described (1,2,3,8,19).

For many of the vitamins which have been investigated thoroughly, a reference standard has been either officially or tentatively adopted. The World Health Organization of the United Nations is the present sponsor of standards which are being used internationally. The biological activity of definite weights of highly purified preparations is accepted as the unit of activity, which is expressed as an International Unit (I.U.). The International Units are the basis for the U.S. Pharmacopeia Units (U.S.P. units) used in the U.S. and for the Medical Research Council Units (M.R.C. units) used in England.

The requirements of vitamins by man and livestock are most important from a practical point of view. The latest and most outstanding efforts at setting up standards for these requirements have resulted in a series of publications by the Food and Nutrition Board and the Committee on Animal Nutrition of the National Research Council. Table IV lists the recommended dietary allowances for humans (13), and Table V the stress requirements for vitamins, in accordance with the National Research Council Report on Therapeutic Nutrition (7).

TABLE V. National Research Council Report on Therapeutic Nutrition.

Vitamin	Daily stress requirements (13), oral dosages
Thiamine	Effect of stress not established; during antibiotic administration, however: 10–25 mg. for first 10 days, 5 mg. maintenance dose thereafter
Riboflavin	10–15 mg. during acute phase, slowly decrease to 1.8 mg.
Niacin	50–100 mg. during severe illness; up to 500 mg. during first 7–10 days of serious depletion
Pyridoxine (B_6)	2 mg. nutritional depletion, burns, etc.
Vitamin B_{12}	2–4 γ during severe illness, radiation injury, etc.
Pantothenic acid	20 mg. nutritional depletion, burns, etc.
Ascorbic acid	300 mg. moderate stress, up to 1000 mg. during acute phase of stress (fractures, etc.)

Table VI lists the domestic animals for which vitamin recommendations have been made.

TABLE VI. Recommendations for Domestic Animals.

Domestic animal	Type	Source
Chickens	0–8 wk.; 8–18 wk.; laying hens; breeding hens	National Research Council Publ. 301, "Nutrient Requirements for Poultry," rev. 1954
Turkeys	0–8 wk.; 8–16 wk.; breeding turkeys	As above
Ducks	Starting and growing ducks	As above
Swine	Market stock of 25–250 lb.; pregnant females and breeding boars; lactating females	National Research Council Publ. 295, "Nutrient Requirements for Swine," rev. Aug. 1953
Dairy cattle	Dairy heifers; mature cows; breeding bulls	National Research Council, "Recommended Nutrient Allowances for Dairy Cattle," rev. April 1950
Beef cattle	Heifers and steers; bulls; wintering weanling calves; wintering yearling cattle; wintering pregnant heifers; wintering pregnant cows; cows nursing calves	National Research Council, "Recommended Nutrient Allowances for Beef Cattle," rev. Dec. 1950
Sheep	Bred ewes, ewes in lactation; lambs and yearlings; fattening lambs	National Research Council, "Recommended Nutrient Allowances for Sheep," rev. Aug. 1949
Horses	Growing and mature horses; pregnant and lactating mares	National Research Council, "Recommended Nutrient Allowances for Horses," March 1949
Fox, Minks		Natural Research Council, "Nutrient Requirements for Foxes and Mink," 1953
Dogs	Dogs by body weight and by breed	National Research Council Publ. 300, "Nutrient Requirements for Dogs," Dec. 1953

FOOD FORTIFICATION

It is agreed by most nutrition scientists that certain steps which have been taken in the field of food fortification such as the vitamin enrichment of flour and bread, the iodization of salt, the addition of vitamin A to table fats, of vitamin D to milk and the vitamin enrichment of animal feeds, have proved advantageous for nutrition and health. At the same time it is recognized that the unlimited fortification of our food supply with specific nutrients can be undesirable. With respect to these considerations, the Council on Foods of the American Medical Association and the Food and Nutrition Board of the National Research Council have issued a "Joint Statement of General Policy in Regard to the Addition of Specific Nutrients to Foods" (10). The requirements for the endorsement of a specific fortification are: (*a*) a clear indication of a probable advantage of an increased consumption of the nutrient in question; (*b*) assurances that the food item concerned would be an effective vehicle of distribution for the nutrient to be added, and (*c*) that such an addition would not be prejudicial to the achievement of a diet good in other respects. The statement favors, as well, the principle of restoration, that is, the replacement of nutrients lost in the refining process up to their natural level rather than beyond that point.

The following endorsements were reaffirmed from an earlier paper (9):

Restoration of processed cereals with thiamine, riboflavin, niacin, and iron.

Enrichment of white bread and flour with thiamine, riboflavin, niacin, and iron.

Fortification of milk with 400 units of vitamin D per quart; of margarine with not less than 9000 units of vitamin A per pound; and of salt with iodine.

See also *Bakery processes and products*, Vol. 2, p. 287; *Cereals*, Vol. 3, p. 626; *Dairy products*, Vol. 4, pp. 789, 822; *Margarine*, Vol. 8, pp. 801, 803.

Table VII lists the range of the amounts of the various ingredients which the Food and Drug Administration has declared as either required or optional in the enrichment program for staple products (5).

TABLE VII. Standards and Proposed Standards for Food Products.

	Required ingredients per pound					
	Thiamine, mg.		Riboflavin, mg.		Niacin, mg.	
Product	Min.	Max.	Min.	Max.	Min.	Max.
Flour	2.0	2.5	1.2	1.5	16.0	20.0
Bread	1.1	1.8	0.7	1.6	10.0	15.0
Corn products	2.0	3.0	1.2	1.8	16.0	24.0
Macaroni products	4.0	5.0	1.7	2.2	27.0	34.0
Farina	1.66	—	1.2	—	6.0	—

	Required iron, mg.		Optional ingredients per pound			
			Calcium, mg.		Vitamin D (U.S.P. units)	
Product	Min.	Max.	Min.	Max.	Min.	Max.
Flour	13.0	16.5	500	625	250	1000
Bread	8.0	12.5	300	800	150	750
Corn products	13.0	26.0	500	750	250	1000
Macaroni products	13.0	16.5	500	625	250	1000
Farina	6.0	—	500	—	250	—

Antivitamins

Antivitamins is a term applied to compounds which act as antagonists to specific vitamins. Thus they belong to the general class of antimetabolites. The concept of antagonists was proposed in 1940 by Woods (20) upon his discovery of the ability of *p*-aminobenzoic acid to counteract the bacteriostatic effect of sulfanilamide. The general theory was developed by Woolley (21), who contributed many of the specific examples of antimetabolites known today. The ratio of the amount of antimetabolite needed to overcome a unit weight of the vitamin is called the *inhibition index*. This index is a constant if the antagonism is competitive. For example, in the case of the PABA-sulfanilamide antagonism the inhibition index is 5000, meaning that it takes 5000 times as much of sulfanilamide as of PABA to obtain inhibition of bacterial growth.

There are many compounds which are vitamin antagonists when measured in tests involving enzymes or microorganisms. Only a few of these, however, are effective antagonists in the animal or in man. The more important ones are summarized in Table VIII, which indicates also the place in this Encyclopedia where some of these compounds have been discussed.

The term antivitamin is applied also to compounds which render a vitamin ineffective either by binding it in such a fashion as to make the vitamin unavailable to the organism, or by converting a vitamin into a compound of different chemical structure. An example of the former type is avidin, the protein present in egg white,

TABLE VIII. Vitamin Antagonists.

Vitamin	Antagonists	Reference
Ascorbic acid	D-Glucoascorbic acid	Vol. 2, p. 159
Thiamine	Oxythiamine, pyrithiamine	Vol. 14, p. 47
Riboflavin	7-Chloro-6-methylriboflavin	—
Nicotinic acid	β-Acetylpyridine, pyridine-3-sulfonic acid	—
Pantothenic acid	ω-Methylpantothenic acid	Vol. 9, p. 809
Biotin	Avidin	Vol. 2, p. 520
Pyridoxine	4-Desoxypyridoxine, methoxypyridoxine, 5-desoxypyridoxal	Vol. 11, p. 305
Folic acid	Aminopterin (4-aminopteroylglutamic acid)	Vol. 6, p. 783
p-Aminobenzoic acid	Sulfanilamide	Vol. 2, p. 472; Vol. 13, p. 280

which binds biotin. An example of the latter type is thiaminase, a group of enzymes which convert thiamine into inactive compounds. There is evidence, for example, that thiamine may be esterified by one enzyme or split into several molecules by one or more different thiaminases.

Although vitamin antagonists are produced commercially only on a small scale, several are being used clinically on an experimental basis. For example, aminopterin and other folic acid antagonists are being explored as chemotherapeutic agents for the regression of tumors, the treatment of leukemia, and other pathological conditions.

Bibliography

(1) A.M.A., Council on Pharmacy and Chemistry, *Tests and Standards for New and Nonofficial Remedies*, 1954.
(2) A.O.A.C., 7th ed., 1950.
(3) Association of Vitamin Chemists, *Methods of Vitamin Assay*, 2nd ed., Interscience, N.Y.-London, 1951.
(4) Drummond, J. C., *Biochem. J.*, **14**, 660 (1920).
(5) Food and Drug Administration, "Service and Regulatory Announcements," Food, Drug and Cosmetic No. 2, rev. 1, June 1951.
(6) Funk, C., *J. State Med.*, **20**, 341 (1912).
(7) Griffith, W. H., Paper presented at American Dietetic Association Meeting, Los Angeles, Calif., August 1953.
(8) György, P., *Vitamin Methods*, 2 Vols., Academic Press, N.Y., 1951.
(9) *J. Am. Med. Assoc.*, **129**, 349 (1945).
(10) *J. Am. Med. Assoc.*, **154**, 145 (1954); *J. Nutrition*, **53**, 623 (1954).
(11) McCollum, E. V., and Davis, M., *J. Biol. Chem.*, **23**, 181 (1915).
(12) Molitor, E. V., and Emerson, G. A., *Vitamins and Hormones*, **6**, 69 (1948).
(13) National Research Council Publ. 302, "Recommended Dietary Allowances," Washington, D.C., rev. 1953.
(14) N.N.R., 1954.
(15) Osborne, T. B., and Mendel, L. B., *J. Biol. Chem.*, **20**, 379 (1915).
(16) Rosenberg, H. R., *Chemistry and Physiology of the Vitamins*, rev. reprint, Interscience, N.Y.-London, 1945.
(17) Sebrell, W. H., Jr., and Harris, R. S., *The Vitamins, Chemistry, Physiology, Pathology*, 3 Vols., Academic Press, N.Y., 1954.
(18) Upjohn Co., *Vitamin Manual*, Kalamazoo, Mich., 1953.
(19) U.S.P. XV, 1955.
(20) Woods, D. D., *Brit. J. Exptl. Pathol.*, **21**, 74 (1940).
(21) Woolley, D. W., *A Study of Antimetabolites*, Wiley, N.Y., 1952.

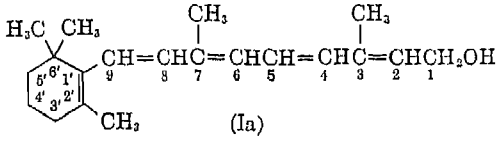
PERIODICALS

(22) *Annual Review of Biochemistry*, Stanford, Calif.
(23) *International Review of Vitamin Research*, Bern, Switzerland.
(24) *Nutrition Reviews*, The Nutrition Foundation, N.Y.
(25) *Nutrition Abstracts and Reviews*, Aberdeen, Scotland.
(26) *Vitamins and Hormones*, Academic Press, N.Y.
(27) *Advances in Enzymology*, F. F. Nord, ed., Interscience, N.Y.-London.

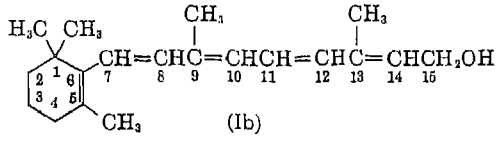
H. R. ROSENBERG AND MOLLIE G. WELLER

VITAMIN A

Vitamin A, $C_{20}H_{30}O$, is an isoprenoid polyene alcohol, all-*trans*-3,7-dimethyl-9-(2,6,6-trimethyl-1-cyclohexen-1-yl)-2,4,6,8-nonatetraen-1-ol (I). It is also known as vitamin A_1 and axerophthol (37); other names, now obsolete, are fat-soluble A,



(Ia)

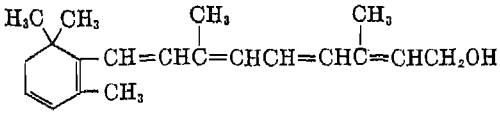


(Ib)

Vitamin A

ophthalamin, biosterol, the antixerophthalmic vitamin, and the anti-infective vitamin. It is characterized physiologically by its ability to produce growth and cure xerophthalmia in vitamin A-deficient rats, but its actual physiological role is presumably much more encompassing and complex. In nature it occurs in the animal organism only, accompanied by minor quantities of a mono-cis isomer, *neovitamin A*. Both isomers have been prepared synthetically. Four additional geometric isomers of vitamin A are now known through synthesis.

A derivative (II) of vitamin A, differing only in the presence of an additional double bond in the ring, occurs in fresh-water fish. It has also been prepared synthetically. Since its physiological properties are comparable to those of vitamin A, it is called *vitamin* A_2. Vitamins A_1 and A_2 are the only known members of the group sometimes referred to as "the vitamins A." The term "vitamin A" used in this sense denotes a naturally occurring compound which fulfills *per se* all the biological functions of vitamin A. A number of synthetic compounds show vitamin A-like activity in producing growth in vitamin A-deficient rats, but these cannot be called "vitamins A" since they do not appear to occur in nature.



(II) Vitamin A_2

Structurally, vitamin A is very closely related to the *carotenoids*, and may be regarded formally as a degradation product of the β-ionylidene carotenoids. These are naturally occurring isoprenoid polyenes composed of 40 carbon atoms and containing a terminal unsubstituted β-ionone ring. In the animal organism they are metabolically degraded to vitamin A and are therefore called *provitamins A*. Both vitamin A and the carotenoids structurally obey the "isoprene rule," but because of their many special features they are not customarily considered terpenoids (see Vol. **13**, p. 705) but rather a class by themselves.

No official **numbering system,** such as that adopted for the carotenoids (see p. 801) exists for vitamin A. The systematic name given above follows the numbering of the Geneva system, shown in (Ia), and is used by *Chemical Abstracts*, but several other different methods of numbering are also currently in use. In view of the close relationship between vitamin A and the carotenoids, the official carotenoid numbering system will be arbitrarily applied to vitamin A, as shown in (Ib), in the subsequent sections; thus 13,14-*cis*-vitamin A corresponds to 2-*cis*-vitamin A (*C.A.*), and 9,10-13,14-di-*cis*-vitamin A to 2,6-di-*cis*-vitamin A (*C.A.*). The methyl groups attached to the ring are shown only in formulas (I) and (II) and are represented by bonds in later formulas.

History (28). In 1913, McCollum and Davis, and, almost simultaneously, Osborn and Mendel, published the results of experiments which showed that rats could not develop normally on a purified diet of proteins, fats, carbohydrates, and minerals unless butter, egg-yolk extract, or cod-liver oil was added. They concluded, therefore, that these substances contained a hitherto unrecognized factor (or factors) indispensable for normal growth and development. Similar experiments and observations had been made earlier (1906–7) by Hopkins in England, but unfortunately the results were not published until much later. The new factor was called "fat-soluble A," to distinguish it from another factor, "water-soluble B," found, shortly afterwards, to be likewise indispensable for normal nutrition.

Another fat-soluble factor, distributed in much the same manner as fat-soluble A (in the non-saponifiable fraction of butter and cod-liver oil) was found in 1919 by Mellanby to be responsible for the prevention of rickets. This new factor was eventually distinguished from fat-soluble A by McCollum, who showed that the growth-promoting activity of cod-liver oil was completely destroyed by aeration at 100 °C. without affecting the antirachitic activity present. (See "Vitamin D.") In 1937 the existence of a second growth-promoting substance was recognized and called vitamin A_2 (14,23).

During the 1920's, in spite of numerous unsuccessful attempts at isolating and chemically identifying vitamin A, the importance of its biological role became well established. Positive correlations between its growth-promoting activity, spectral extinction at 325–328 mμ, and the intensity of the blue color formed with antimony trichloride permitted a reasonably accurate estimation of the vitamin without resorting to the laborious bioassay. Much richer sources than cod liver were found in other fish, especially halibut, from which concentrates containing at least 50% of the vitamin could be made.

It was first demonstrated by Steenbock, in 1920, that *carotene* ($C_{40}H_{56}$), a normal constituent of plants, can adequately replace vitamin A in the diet. Subsequently, many varieties of vegetables were found to be potent sources of vitamin A activity. In 1930 Moore unequivocally demonstrated the conversion of β-carotene to vitamin A in rats, thereby establishing the role of certain carotenoids as provitamins A. Chemical degradation studies of β-carotene and of vitamin A, going on in other laboratories at the same time, led to the recognition of the intimate chemical relationship between the two, and in 1931 the correct structural formulas for the two compounds were proposed by Karrer (42). That of vitamin A was shortly afterwards confirmed by Karrer by identifying a specimen of fully hydrogenated vitamin A with perhydrovitamin A obtained by synthesis (41). The formula of β-carotene was later confirmed by other workers.

A crystalline form of vitamin A was first isolated by Holmes and Corbet in 1937 as a monomethanolate (31). The pure unsolvated form and several of its pure crystalline esters were eventually obtained by Baxter and Robeson in 1942 (6). Crystalline neovitamin A was isolated in 1946 by the same workers (57).

Isler and his co-workers (1947) (34) were the first to synthesize the pure crystalline vitamin. Previous syntheses by Kuhn in Germany (1937) (44) and Milas in the U.S. (1940) (48) yielded impure

though biologically active products. In 1950 the synthesis of β-carotene was reported by Karrer in Switzerland and Inhoffen in Germany (33).

Vitamin A and Cis Isomers

As a growth-promoting substance, vitamin A is the most potent stereoisomer (all-trans) of (I) and is more active than any synthetic vitamin A-like or provitamin A compound now known.

PROPERTIES OF VITAMIN A

Vitamin A is a pale yellow crystalline solid, m.p. 62–64 °C., which can be purified by crystallization from ethyl formate or petroleum ether at low temperatures (6, p. 2411). It crystallizes from methanol as the monomethanolate, m.p. 8 °C. (31). Vita-

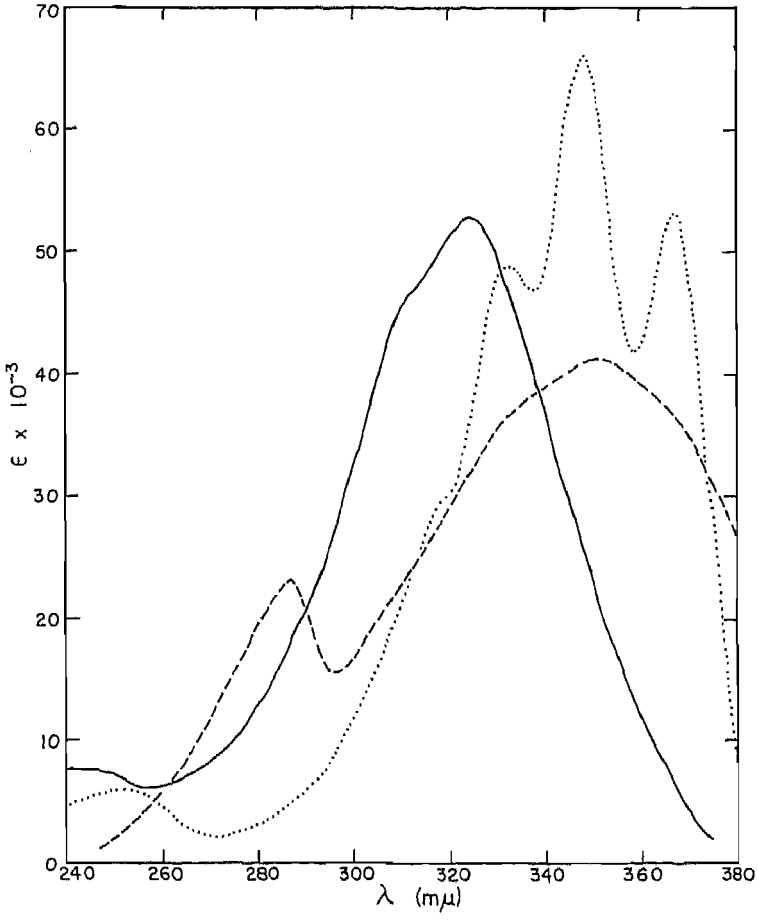


Fig. 1. Ultraviolet absorption curves in 95% ethanol of vitamin A (solid curve), vitamin A_2 (broken curve), and retrovitamin A (dotted curve).

min A is insoluble in water but dissolves readily in the usual fat solvents. The partition coefficient between petroleum ether and 83% ethanol is 0.82 (15). It is readily adsorbed on alumina, magnesia, and other neutral or alkaline adsorbents, making possible its isolation from mixtures by chromatography. Acidic adsorbents destroy it. It fluoresces in ultraviolet light.

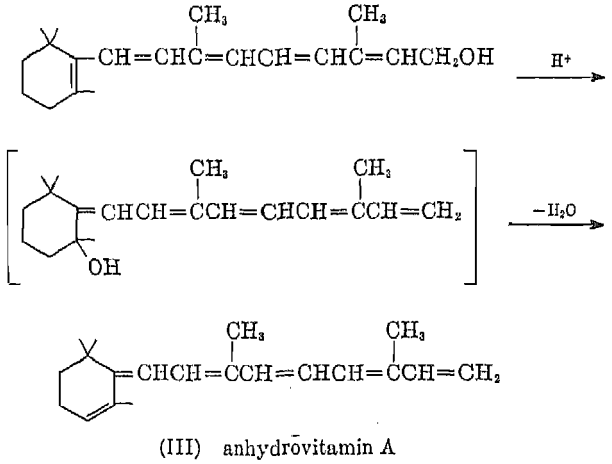
Vitamin A shows a very characteristic ultraviolet absorption spectrum, which consists of a single-peaked absorption band, $\lambda_{max.}^{C_2H_5OH}$ 325 mμ, $E_{1\ cm.}^{1\%}$ 1,830, ε 52,800 (59), rather than the usual triple-peaked band of conjugated polyene alcohols and hydrocarbons (Fig. 1). Its absorption maximum is considerably displaced toward the shorter wave lengths from that usually shown by equally substituted conjugated pentaenes. These unique spectral features of vitamin A are due to steric hindrance in the molecule between one of the 1-methyl groups and the 8-hydrogen. Such hindrance is present in all β-ionylidene compounds (52).

Reactions. As a conjugated polyene, vitamin A shows the usual reactions of conjugated double bonds. It is oxidized readily by atmospheric oxygen, especially in the presence of light and heat. In an inert atmosphere it still deteriorates in ultraviolet light but is quite stable to heat, and can be distilled in high vacuum, $b_{0.005}$ 120–125°C. (30). Oil solutions can be stabilized toward oxidation by means of antioxidants such as α-tocopherol (see "Vitamin E"). The last two double bonds of the side chain readily participate in a Diels-Alder reaction with maleic anhydride (59) (see Vol. 8, p. 682). Catalytic hydrogenation yields the biologically inactive perhydro compound.

As a primary alcohol, it readily forms esters and ethers, which can be used for characterization: acetate, m.p. 57–58°C.; palmitate, m.p. 27–28°C.; *p*-phenylazobenzoate, m.p. 79–80°C. (6, p. 2407); anthraquinone-2-carboxylate, m.p. 122–123°C. (57); of the known ethers, only the methyl, m.p. 34–35°C., and the phenyl, m.p. 90–92°C., are solids (35). The esters and ethers are more stable than the free alcohol. The acetate is the basis of definition of the International and U.S.P. units of biological activity (see p. 807).

Vitamin A is not affected by alkali, but because of the allylic nature of its hydroxyl group it very readily rearranges and dehydrates in the presence of acids (see Scheme 1), yielding *anhydrovitamin A* (III) (47,63). This is an orange-yellow crystalline conjugated hexaene showing intense absorption bands in the ultraviolet, $\lambda\lambda_{max.}^{C_2H_5OH}$ 350, 368, and 389 mμ. It is very frequently encountered in various chemical manipulations of vitamin A, especially when acids, even in traces, are present. It almost always appears as an artifact in the chromatography of vitamin A. The esters and ethers undergo the same reaction.

SCHEME 1



(III) anhydrovitamin A

Oxidation with manganese dioxide yields the corresponding aldehyde, *all-trans-retinene* (3,7-dimethyl-9-(2,6,6-trimethyl-1-cyclohexen-1-yl)-2,4,6,8-nonatetraenal (*C.A.*)) (4), m.p. 57, 65°C. (dimorphic forms), $\lambda_{max.}^{C_2H_5OH}$ 381 mμ, ε 43,400 (58). This aldehyde occurs naturally in retinas. The corresponding acid, *vitamin A acid*, has m.p. 182°C., $\lambda_{max.}^{C_2H_5OH}$ 348 mμ, ε 45,000 (59).

With antimony trichloride in chloroform solution, vitamin A gives a characteristic blue color, $\lambda_{max.}^{CHCl_3}$ 620 mμ (Carr-Price test), which is the basis of an analytical procedure (see p. 809). Other inorganic halides, like arsenic trichloride, stannic chloride, boron trifluoride, and certain acid earths also give intense colors with vitamin A.

On treatment with catalytic quantities of iodine, vitamin A is partially stereoisomerized to neovitamin A (see below). The ratio of the two isomers at equilibrium is approximately 7 all-trans:3 neo (57).

PROPERTIES OF CIS ISOMERS

Of the known cis isomers of vitamin A, three are "unhindered" and two are "hindered" (see p. 805).

13,14-*cis*-Vitamin A (Neovitamin A) (57,59). This isomer shows about 75% of the biological potency of vitamin A in the rat-growth test (1). It is a pale-yellow crystalline solid, m.p. 58–59°C.; *p*-phenylazobenzoate, m.p. 94–96°C.; anthraquinone-2-carboxylate, m.p. 134–136°C. Its ultraviolet absorption curve, $\lambda_{max.}^{C_2H_5OH}$ 328 mμ, $E_{1\,cm.}^{1\%}$ 1,690, ε 48,300, is very similar to that of vitamin A. The shift of its absorption maximum to a higher wave length is characteristic of polyenes having a terminal cis configuration (53). The physical and chemical properties of neovitamin A are similar to those of vitamin A, but some of its reactions, such as the formation of anhydrovitamin A (III) and the condensation with maleic anhydride, are much slower as a consequence of the terminal cis configuration. The latter reaction makes possible its estimation in mixtures with vitamin A. Oxidation with manganese dioxide yields *13,14-cis-retinene* (neoretinene), m.p. 77°C., $\lambda_{max.}^{C_2H_5OH}$ 375 mμ, ε 35,600 (58). The corresponding *13,14-cis-vitamin A acid* (neovitamin A acid) has m.p. 174–175°C., $\lambda_{max.}^{C_2H_5OH}$ 354 mμ, ε 39,800. The Carr-Price test gives the same blue color observed with vitamin A.

Neovitamin A can be separated from vitamin A by chromatography, being less strongly adsorbed than vitamin A on alumina, magnesia, or sodium aluminum silicate. It can be stereoisomerized to vitamin A by catalytic quantities of iodine, which produces the same equilibrium mixture of the two isomers that is obtained from vitamin A (see above).

9,10-*cis*-Vitamin A (59). This isomer shows only about one-quarter the biological potency of vitamin A (1). It is a pale-yellow crystalline solid, m.p. 81.5–82.5°C.; *p*-phenylazobenzoate m.p. 79–80°C. Its ultraviolet absorption curve shows a single-peaked absorption band, $\lambda_{max.}^{C_2H_5OH}$ 323 mμ, ε 42,300, and a small cis-peak around 260 mμ. Since neither of the last two double bonds of the side chain is cis, reaction with maleic anhydride is fast as compared to neovitamin A. Oxidation with manganese dioxide yields *9,10-cis-retinene*, m.p. 64°C., $\lambda_{max.}^{C_2H_5OH}$ 373 mμ, ε 36,100 (58). The corresponding *9,10-cis-vitamin A acid* has m.p. 189–191°C., $\lambda_{max.}^{C_2H_5OH}$ 345 mμ, ε 36,900. The Carr-Price color is the same as observed with the previous isomers. Catalysis in the dark with iodine does not appear to affect the 9,10-cis configuration.

9,10–13,14-di-*cis*-Vitamin A (59). This isomer has the same biological potency as the 9,10-cis isomer (1). It is a pale-yellow crystalline solid, m.p. 58–59°C.; *p*-phenylazobenzoate, m.p. 91.5–92.5°C. Its ultraviolet absorption curve, $\lambda_{max.}^{C_2H_5OH}$ 324 mμ, ε

39,500, cis-peak about 260 mμ, is very similar to that of the 9,10-cis isomer. Reaction with maleic anhydride is relatively slow because of the terminal cis configuration. Oxidation with manganese dioxide yields the corresponding *di-cis-retinene*, m.p. 49, 85°C. (dimorphic forms), $\lambda_{max.}^{C_2H_5OH}$ 368 mμ, ε 32,400 (58). The corresponding *di-cis-vitamin A acid* has m.p. 135–136°C., $\lambda_{max.}^{C_2H_5OH}$ 346 mμ, ε 34,500. The Carr-Price color is the same as observed with the previous isomers. Catalysis with iodine in the dark produces an equilibrium mixture with the 9,10-mono-cis isomer above.

11,12-*cis*-Vitamin A (55). This is a sterically hindered cis isomer (see p. 805). It has less than 3% of the biological potency of vitamin A. It is a pale-yellow oil; *p*-phenylazobenzoate, m.p. 99–100°C.; anthraquinone-2-carboxylate, m.p. 139–140°C. Its ultraviolet absorption curve shows a single-peaked band, $\lambda_{max.}^{C_2H_5OH}$ 312 mμ, ε 26,000. Iodine catalysis completely inverts the 11,12-cis configuration, and vitamin A can be isolated from the mixture as the major product.

7,8-*cis*-Vitamin A (55). This is also a sterically hindered cis isomer (see p. 805) showing about one-quarter the biological potency of vitamin A (1). It is a pale-yellow oil, $\lambda_{max.}^{C_2H_5OH}$ 322 mμ, ε 26,900, obtained by reducing the carbonyl group of the corresponding *7,8-cis-retinene* (neoretinene b (32, 58)), m.p. 64.5°C., $\lambda_{max.}^{C_2H_5OH}$ 376 mμ, ε 24,300, with sodium borohydride or lithium aluminum hydride (12). Neoretinene b is obtained by irradiating all-*trans*- or neoretinene with visible light. Other workers (58,59) consider neoretinene and its corresponding alcohol to have an 11, 12-13, 14-di-cis configuration.

OCCURRENCE

Vitamin A occurs naturally only in animals, both land and marine. It is distributed in many organs, but is usually concentrated in the liver as an ester of higher fatty acids (11). Animal products such as milk, cream, butter, cheese, and eggs are im-

TABLE I. Vitamin A Values of Some Typical Foods.[a]

Food	I.U. per 100 g.[b,c]	Food	I.U. per 100 g.[b,c]
Cereals		Fruits	
Wheat	0	Oranges	170
Rice	0	Apricots	2,500
Rye	0	Mangoes	1,900
Barley	0	Persimmons	1,900
Oats	0	Cantaloupe	1,200
Corn	450	Animal Products	
Vegetables		Beef	50
Tomatoes	700	Veal	30
Cabbage	100	Pork	0
Broccoli	3,500	Lamb	Negligible
Carrots	2,000	Chicken	400
Spinach	9,400	Turkey	600
Dandelion greens	10,000	Fresh fish (all)	Negligible–100
Kale	7,600	Lobster, shrimp	1,000
Beans (snap or string)	400	Eggs	1,000
Potatoes (white)	0	Dairy products	
Sweet potatoes	500	Milk	100
		Cream	800
		Cheese (Cheddar)	1,400
		Butter	3,200
		Ghee	2,500

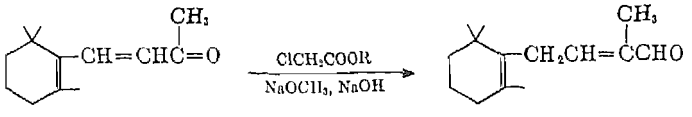
[a] For the vitamin A content of fish-liver oils see Vol. 6, p. 570.
[b] Calculated on basis of the carotene content. Vitamin A content added when present.
[c] Edible portion only.

portant food sources (see Table I) (19) but not industrial sources. Until realization of its commercial synthesis, fish-liver oils constituted the most important industrial source of vitamin A. Salt-water fish are richest, generally containing both all-*trans*- and neo-vitamin A approximately in the ratio of 65:35 (57). There is no evidence that any other stereoisomers of vitamin A occur in nature. Fresh-water fish contain, in addition, vitamin A_2. In some species the oils from the viscera are richer in the vitamin than the liver oils. For further descriptive details and methods of isolating and concentrating the vitamin see *Fish-liver oils*.

SYNTHESIS OF VITAMIN A AND ITS STEREOISOMERS

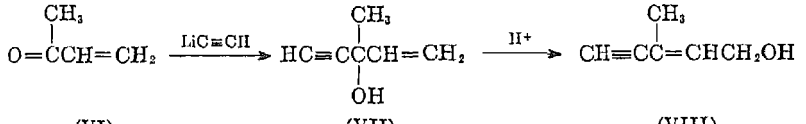
Vitamin A can now be synthesized by a number of methods. A comprehensive review covering the various approaches and the chemistry involved has been written by Baxter (5). The commercial method most widely used today is that shown in Scheme 2. This approach was originally proposed by Heilbron in England (1942) (27)

SCHEME 2



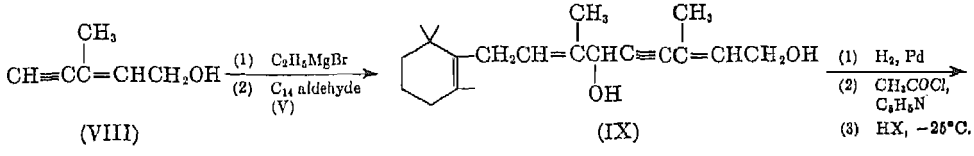
(1)

(IV) β-ionone (V) "C_{14} aldehyde"

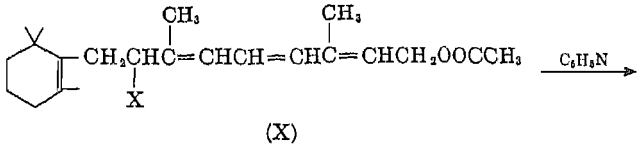


(2)

(VI) (VII) (VIII)

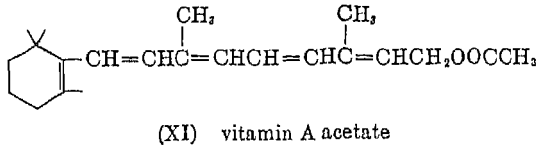


(VIII) (IX)



(X)

(3)



(XI) vitamin A acetate

but was first successfully carried out by Isler of Switzerland (1947) (34). Earlier (48), a somewhat different form of this synthesis was conceived and carried out by Milas in the U.S.

The starting material in equation (1), β-ionone (IV), is a well-known commercial product employed for many years in the perfume industry (see Vol. **10,** p. 23; Vol. **13,** p. 717). This is condensed in a Darzens reaction with methyl or ethyl chloroacetate. The resulting glycidic ester (not shown in Scheme 2) is simultaneously hydrolyzed, decarboxylated, and rearranged to the "C_{14} aldehyde" (V) by the unique method of simply stirring the crude Darzens reaction mixture with methanolic alkali at 5°C. The high yield of aldehyde obtained in this way (80%) is one of the features of this synthesis that helped make it commercially practical. Next, methyl vinyl ketone (VI) is condensed in liquid ammonia with lithium acetylide to yield ethynylmethylvinylcarbinol (3-methylpent-1-en-4-yn-3-ol, VII). This is allylically rearranged in dilute acid to 3-methylpent-2-en-4-yn-1-ol (VIII) (equation (2)). Conversion of (VIII) to the Grignard reagent by means of ethylmagnesium bromide, followed by condensation with the "C_{14} aldehyde" (V) gives the carbon skeleton of vitamin A (IX) (equation (3)). The acetylenic bond is then selectively semihydrogenated by means of a specially poisoned palladium catalyst. Acetylation of the primary hydroxyl group of the glycol (IX) in the next step to the monoacetate prior to the final dehydration is vital to the achievement of a good yield of vitamin A. The glycol monoacetate (not shown) is shaken in chloroform solution at −25°C. with concentrated hydrochloric or hydrobromic acid, and the resulting acetoxy halide (X) then treated with a weak base such as pyridine to remove the elements of hydrochloric or hydrobromic acid, thus forming the fifth double bond. The viscous sirup obtained is dissolved in anhydrous ethyl formate or ethyl alcohol, from which crystals of vitamin A acetate (XI) are deposited on cooling. The free alcohol is then obtained by alkaline hydrolysis of the acetate. The yields in each step commencing with the condensation of (V) and (VIII) are reported to be better than 80% (34,35,75–79).

Market Forms. Vitamin A is marketed as the crystalline alcohol and acetate or as the liquid palmitate either in neat (undiluted) form or as stabilized vegetable oil concentrates. A stabilized powder form used widely today has been achieved by coating the dry acetate with a very thin layer of gelatin (9). *Oleovitamin A*, U.S.P. XV, N.N.R., is a vegetable or fish-oil solution of vitamin A or its esters, either natural or synthetic. Many methods are also available for dispersing vitamin A into aqueous media(74,77); these dispersions are sold as *water-miscible vitamin A*, U.S.P. XV, N.N.R.

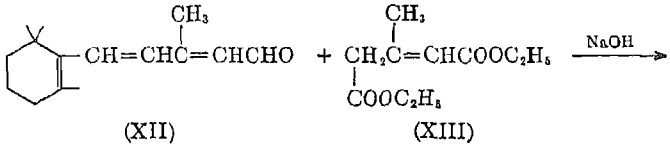
TABLE II. Production and Price Trends of Vitamin A (Pharmaceutical Grade).

Year	Amount produced, in billion units— alcohol and esters	Price range in cents per million units	
		Natural	Synthetic
1949	—	50–30	55–43
1950	26,890	28–16	40–17
1951	67,167	17–14	18
1952	73,322	15	15
1953	106,946	15–12	15–12
1954	—	12	12

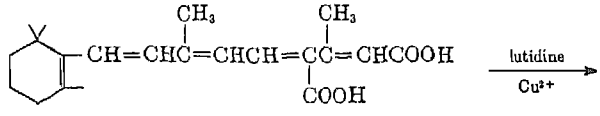
Prices and Production. The appearance of the synthetic product on the market in 1949 has caused a steady drop in price from 55 cents per million units in that year to 12 cents per million in 1955. Production and price trends are shown in Table II. It is estimated that 80% of all the vitamin A produced today is synthetic.

13,14-*cis*-Vitamin A (Neovitamin A). This isomer is the sole product of the reaction sequence shown in Scheme 3 when 9,10-*trans*-β-ionylideneacetaldehyde (3-methyl-5-(2,6,6-trimethyl-1-cyclohexen-1-yl)-2,4-pentadienal) (XII) is the starting material (59). On condensation with either *cis*- or *trans*-β-methylglutaconic ester

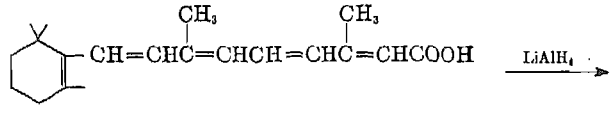
SCHEME 3



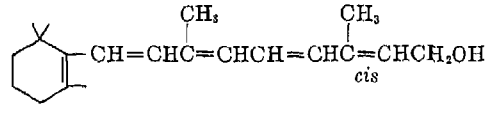
(XII) (XIII)



(XIV)



(XV)



(XVI) neovitamin A

(XIII), this yields a single stereoisomer of 12-carboxyvitamin A acid (XIV). The 12-carboxyl group is then removed by heating in lutidine containing catalytic quantities of copper acetate. The product consists solely of neovitamin A acid (XV), which is readily reduced to neovitamin A (XVI) with lithium aluminum hydride.

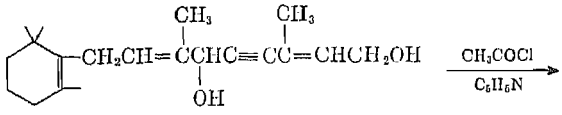
9,10-*cis*-Vitamin A. This can be obtained by reducing the corresponding *cis*-vitamin A acid with lithium aluminum hydride (59).

9,10-13,14-di-*cis*-Vitamin A. By starting with the 9,10-cis isomer of (XII) and employing the reaction sequence shown in Scheme 3, the 9,10-13,14-di-cis isomer is obtained as the sole product (59).

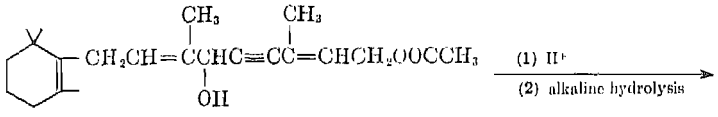
11,12-*cis*-Vitamin A (XIX). This isomer can be obtained by the reaction sequence shown in Scheme 4, which starts with the acetylation of (IX). The dehydration of the monoacetate (XVII) is carried out in boiling benzene containing a catalytic quantity of *p*-toluenesulfonic acid. The semihydrogenation of the resulting 11,12-dehydrovitamin A (XVIII) can be effected with a poisoned Raney nickel or palladium catalyst. The product is isolated and purified by chromatography on alumina (55).

7,8-*cis*-Vitamin A. This isomer can be synthesized by the stereoisomerization of all-*trans*-retinene to 7,8-*cis*-retinene (neoretinene b) (see p. 796), followed by the reduction of this product to the alcohol (12).

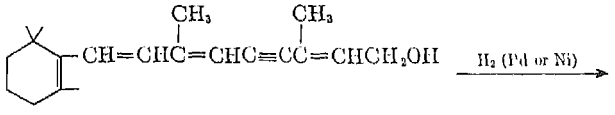
SCHEME 4



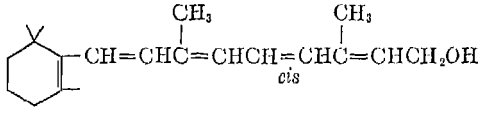
(IX)



(XVII)



(XVIII)



(XIX) 11,12-*cis*-vitamin A

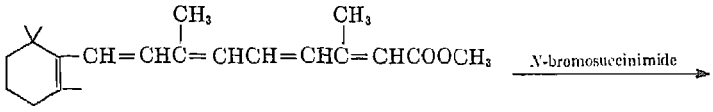
Vitamin A_2

Vitamin A_2 has 40% of the biological potency of vitamin A (62). Although it can adequately replace the latter in the rat-growth test, there is no indication up to the present that it plays any significant role in mammalian nutrition. It occurs in the eyes, livers, viscera, and intestines of fresh-water fish. Its intimate chemical relationship to vitamin A was realized early, but the difficulty in isolating the pure material seriously hampered work on its chemical structure. Its empirical formula, $C_{20}H_{28}O$, was first demonstrated by Shantz (1948), who was able to prepare a pure crystalline *p*-phenylazobenzoate, m.p. 76–77°. On hydrolysis this ester yielded the first pure specimen of vitamin A_2, as a viscous orange-yellow oil (61).

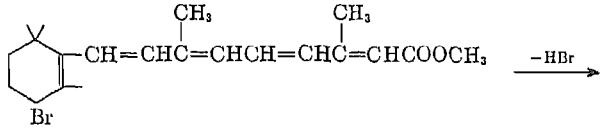
The structure of vitamin A_2 was shown to be 3,4-dehydrovitamin A (II) by Jones and his co-workers through synthesis (1951) (18). This was accomplished, as shown in Scheme 5, by brominating the methyl ester of vitamin A acid (XX), dehydrobrominating the resulting ring bromo compound (XXI) with 4-phenylmorpholine, and reducing the methyl ester of vitamin A_2 acid (XXII) thus obtained with lithium aluminum hydride. The synthetic product, a viscous yellow oil, proved to be identical with the natural material obtained by Shantz.

The ultraviolet absorption curve of the purest natural material shows $\lambda_{max.}^{C_2H_5OH}$ 287 mμ, ϵ 23,300, and 351 mμ, ϵ 41,500; the synthetic product shows two peaks, $\lambda_{max.}^{C_2H_5OH}$ 288 mμ, ϵ 21,900, and $\lambda_{max.}^{C_2H_5OH}$ 352, ϵ 41,300. The Carr-Price color shows maximal absorption at 693 mμ. Vitamin A_2 is much more sensitive to air than vitamin A as a consequence of its additional double bond. Like vitamin A, it is very sensitive to acids. The product obtained on treatment with acids (ethanolic hydrogen chloride)

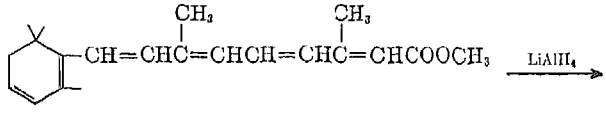
SCHEME 5



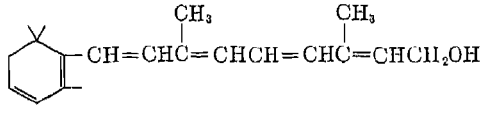
(XX)



(XXI)



(XXII)

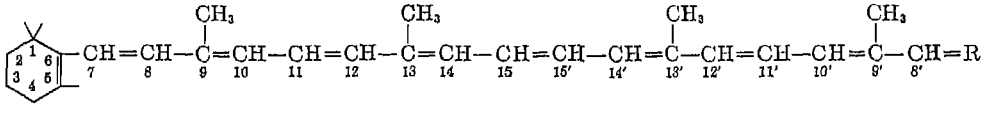


(II) vitamin A_2

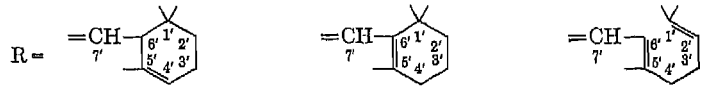
was assumed for many years to be anhydrovitamin A_2, the conjugated heptaene analog of (III), but recently Jones has shown that it is actually 3-ethoxyanhydrovitamin A (29). Oxidation of vitamin A_2 with manganese dioxide yields *retinene*$_2$, m.p. 77–78°C., $\lambda_{max.}^{C_6H_{12}}$ 388 mμ, ε 41,100. This aldehyde occurs naturally in the retinas of fresh-water fish (66).

The Provitamins A

No official definition exists for a provitamin A. Usage has confined the term to those naturally occurring carotenoids which are transformed *in vivo* to vitamin A and, as a consequence, possess vitamin A activity (60). The Council on Pharmacy and Chemistry of the American Medical Association regards the term "provitamin A" as a synonym for α-, β-, or γ-carotene, N.N.R. (XXIII) and for cryptoxanthin (3-



(XXIII) Carotene



α β γ

hydroxy-β-carotene) (50), but these are not the only carotenoids that show provitamin A activity (see Table III). In the broad sense, any compound that can be converted in the animal body to vitamin A should be called a provitamin A. This would include such products as β-apo-2-carotenal and retinene, which have definitely been proved to yield vitamin A *in vivo* (17,24). Many other biologically active degradation products of β-ionylidene carotenoids are undoubtedly also provitamins A. A number of active synthetic analogs, homologs, and derivatives of vitamin A and of β-carotene have been referred to as provitamins A in some of the literature, but such classification should be deferred until it is shown whether these compounds are converted *in vivo* to vitamin A or are active *per se*.

TABLE III. Provitamin A Carotenoids.

Compound	Empirical formula	Source	Percentage of vitamin A activity per mole
α-Carotene	$C_{40}H_{56}$	Most plants	54 (72)
β-Carotene	$C_{40}H_{56}$	Most plants	100 (72)
γ-Carotene	$C_{40}H_{56}$	Carrots (rare)	42 (72)
Cryptoxanthin	$C_{40}H_{56}O$	Yellow corn, butter	57 (72)
Aphanin	$C_{40}H_{54}O$	Blue algae	50 (40)
Aphanicin	$C_{40}H_{56}O$	*Aphanizomenon flosaquae*	26 (40)
Myxoxanthin	$C_{40}H_{54}O$	Blue algae	Active (40)
Echinenone	$C_{40}H_{38}O$(?)	Sea urchin	Active (40)
Torularhodin	$C_{37}H_{48}O_2$	Red yeast	Active (40)
Mutatochrome (citroxanthin)	$C_{40}H_{56}O$	Orange peels	Active (40)
α-Carotene epoxide	$C_{40}H_{56}O$	*Ranunculus acer*	Active (40)

The **carotenoids** are yellow to red polyene pigments occurring in all green tissues of plants as well as in many species of fungi, bacteria, and algae. They also occur in animals, which acquire them by ingestion of vegetable products. Carotenoids are not synthesized in the animal organism. A very comprehensive review of the chemistry of the carotenoids has been written by Karrer (40) and one on their biochemistry by Goodwin (25).

Structurally, the carotenoids are characterized by a long polyene chain composed of recurring 2-methyl-2-butene units ("isoprene units") linearly joined to each other by double bonds. The center of the molecule always consists of two such units joined "tail-to-tail." In the C_{40} carotenoids, two additional units are joined to the center portion in a head-to-tail fashion with the resulting polyene chain then ending in various combinations of citrylidene and α- and β-cyclocitrylidene groups, as well as oxygenated derivatives of these. (See Vol. **13**, pp. 705, 716–17.) The lower carotenoids (bixin, C_{24}; crocetin, C_{20}) are dicarboxylic acids and may be regarded as symmetrical degradation products of C_{40} precursors.

The **numbering system** shown in formula (XXIII) was originally proposed by Karrer and has been officially adopted by the International Union of Pure and Applied Chemistry (36) and by the Committee on Biochemical Nomenclature of the National Research Council (10). According to this last report, aldehydic and ketonic fragments obtained from the degradation of carotene receive the "-al" and "-one" suffixes only when given the prefix "apo-." This prefix is usually followed by a number, which indicates the double bond, counting the ring double bond as 1 or 1′, at which the carotenoid molecule was broken. Thus β-apo-2-carotenal is the aldehyde formed when the C(8′)-C(7′) double bond of carotene is ruptured. However, instead of using separate numbers to refer to

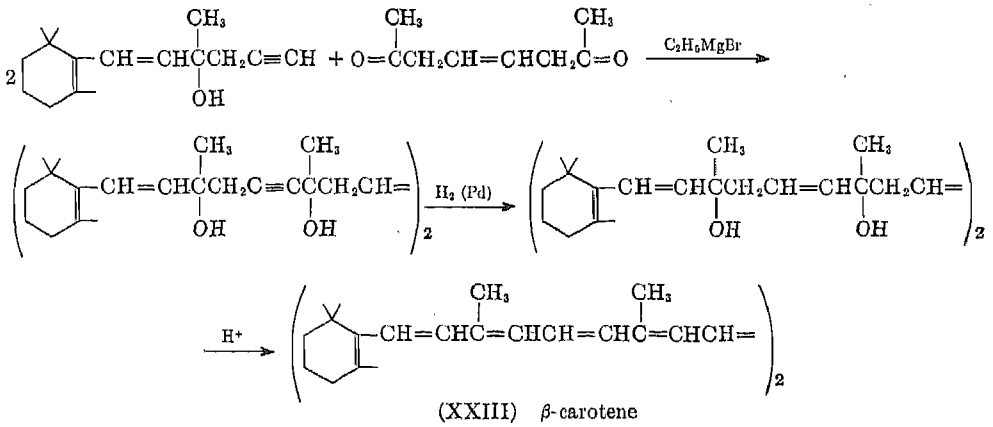
the double bonds, it is now recommended that "apo-" be preceded by a number indicating the carbon atom of the ketonic or aldehydic group. Thus β-apo-2-carotenal would be β-8′-apocarotenal.

The biologically active carotenoids and their sources are listed in Table III (see also *Cereals*, Vol. **3,** p. 620). The prime essentials for provitamin A activity are an unsubstituted β-ionone ring and an unsaturated side chain equivalent at least to that of vitamin A. The only exceptions to this rule are the carotenoid epoxides. The activity of these derivatives is presumed to be due to the ability of the animal organism to remove the epoxide group (40).

The fact that **β-carotene** (XXIII), the most active provitamin A, consists of two vitamin A moieties symmetrically linked at their terminal side-chain carbons led to the postulation that the provitamin A carotenoids owe their activity to *in vivo* cleavage at the 15,15′-double bond in the center of the molecule. Although β-carotene should on this basis give rise to two molecules of vitamin A, the preponderance of bioassay data show only one molecule of vitamin A to be metabolically available. Present international activity standards therefore show a 1:2 relationship between vitamin A and β-carotene on a weight basis and approximately a 1:1 relationship on a molar basis. (A recent study has been reported indicating that quantitative fission of β-carotene to vitamin A may occur *in vivo* if the correct amount of α-tocopherol is present (43). This has not yet been confirmed by other workers.) The fact that those carotenoids having only one unsubstituted β-ionone ring show at most only half the activity of β-carotene lends support to the theory of central fission *in vivo*. It has been pointed out, however, that all such carotenoids should show an activity equivalent to that of α-carotene, whereas in fact there are significant differences. Whether this is due to some inherent property of these molecules or to the uncertainties of the bioassay is still a question that remains to be settled.

Economically, the most important provitamin A carotenoid is β-carotene. It is the most widely distributed carotenoid in nature, and has been found in the leaves of all plant species so far examined. The all-trans isomer is a dark-red crystalline solid, m.p. 181–182°C., showing a characteristic absorption spectrum, $\lambda\lambda_{max.}^{CS_2}$ 450, 485, and 520 mμ. It gives a characteristic blue color, $\lambda_{max.}^{CHCl_3}$ 590 mμ, in the Carr-Price reaction and shows the typical reactions of conjugated double bonds, that is, sensitivity to oxygen, light, heat, etc. It is soluble in the usual fat solvents.

SCHEME 6

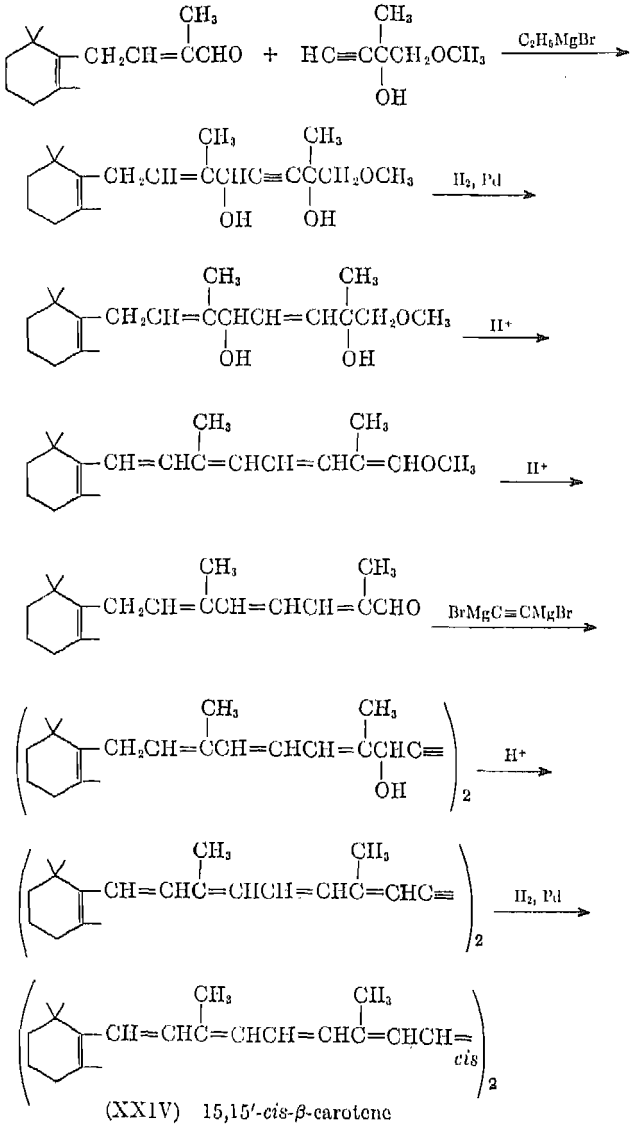


(XXIII) β-carotene

Numerous procedures for its isolation from plants have been developed and patented. For the most part these consist of solvent extraction of dried carrots, alfalfa, leaf wastes, or other dried vegetable residue, and of selective adsorption on materials like activated carbon, magnesia, or tricalcium phosphate. Palm oil is also an important industrial source.

β-Carotene has been synthesized both by Karrer in Switzerland (33) (Scheme 6) and by Inhoffen in Germany (33) (Scheme 7).

SCHEME 7



(XXIV) 15,15′-*cis*-β-carotene

(XXIII) all-*trans*-β-carotene

Crude β-carotene mixed with its isomers has been available for use in animal feeds. Pure β-carotene obtained from natural sources has been available in very small quantities for research purposes. Recently the Hoffmann-La Roche Company has put on the market pure synthetic β-carotene both as the crystalline material and as a semisolid suspension in vegetable oil.

Stereochemical Aspects of the Vitamins and Provitamins A

The four double bonds in the vitamin A or vitamin A_2 side chain theoretically permit sixteen possible geometric isomers, and the nine in the side chain of β-carotene allow for 272. In the unsymmetrical molecule, α-carotene, 512 geometric isomers can be formulated. For many years it was assumed that a cis configuration of type I (Fig. 2) in an isoprenoid polyene would be too unstable (because of the steric hindrance involved) to be capable of existence. Therefore only cis configurations of type II (Fig. 2), as well as that involving the central double bond in the carotenoids, were considered possible. This limited the number of expected stereoisomers of vitamin A, β-carotene, and α-carotene to 4, 20, and 32, respectively (71).

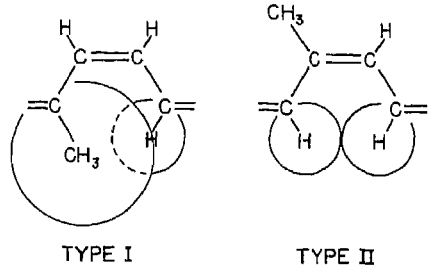


Fig. 2. The types of cis configuration possible in isoprenoid polyenes.

However, it was recently shown by synthesis that these "forbidden" cis configurations in isoprenoid polyenes are not only possible but are considerably more stable than had been presumed (21,52,53). This finding reestablished 16 and 272 as the maximum number of stereoisomers that may theoretically be expected for the vitamins A and β-carotene, respectively.

To date, all three possible "unhindered" cis isomers of vitamin A are known as well as two "hindered" cis isomers, the 7,8-cis and 11,12-cis; see Fig. 3. (The hindrance normally present in the β-ionylidene group is ignored in these considerations.) (See p. 799.) The 7,8-cis isomer is thought to play a key role in vision. No stereoisomers of vitamin A_2 have been isolated, but there is evidence for the existence of a 13,14-cis isomer (*neovitamin* A_2) (18).

The carotenoids exist in nature predominantly in the all-trans form, but a considerable number of cis isomers have been isolated from natural sources. Notable among these are the polycis isomers prolycopene and pro-γ-carotene (11, ch. VII). Additional cis isomers have been obtained by stereoisomerization of the naturally occurring isomers. This is generally accomplished by the action of light, heat, catalytic quantities of iodine or acids, or, in some cases, simply by solution in inert solvents. The mixture of stereoisomers obtained is then separated into its components by chromatography on suitable adsorbents. Deduction of the steric configurations can be made from the changes in the ultraviolet absorption spectra (71).

The above methods of stereoisomerization usually affect only the unhindered type II configurations. The only exception to this rule that has so far been found is the photoisomerization of all-*trans*-retinene or neoretinene to 7,8-*cis*-retinene, a type I cis isomer (32).

Some cis isomers can be obtained by stereospecific syntheses. In the vitamin A

group this is illustrated by the synthesis of neovitamin A (Scheme 3) and 9,10-*cis*-vitamin A, whereby type II cis configurations are introduced; and by the synthesis of 11,12-*cis*-vitamin A (Scheme 4), whereby a type I cis configuration is achieved. The method in the latter case, that is, the selective catalytic semihydrogenation of an acetylenic bond, is that generally used for introducing a type I cis configuration as well as an unhindered cis —CH=CH— double bond into a compound (7,52,53). By this technique Karrer was able to prepare the sterically hindered 11,12-11′,12′-di-*cis*-β-carotene (21), and Inhoffen the 15,15′-*cis*-β-carotene (central mono-*cis*-β-carotene, Scheme 7) (33).

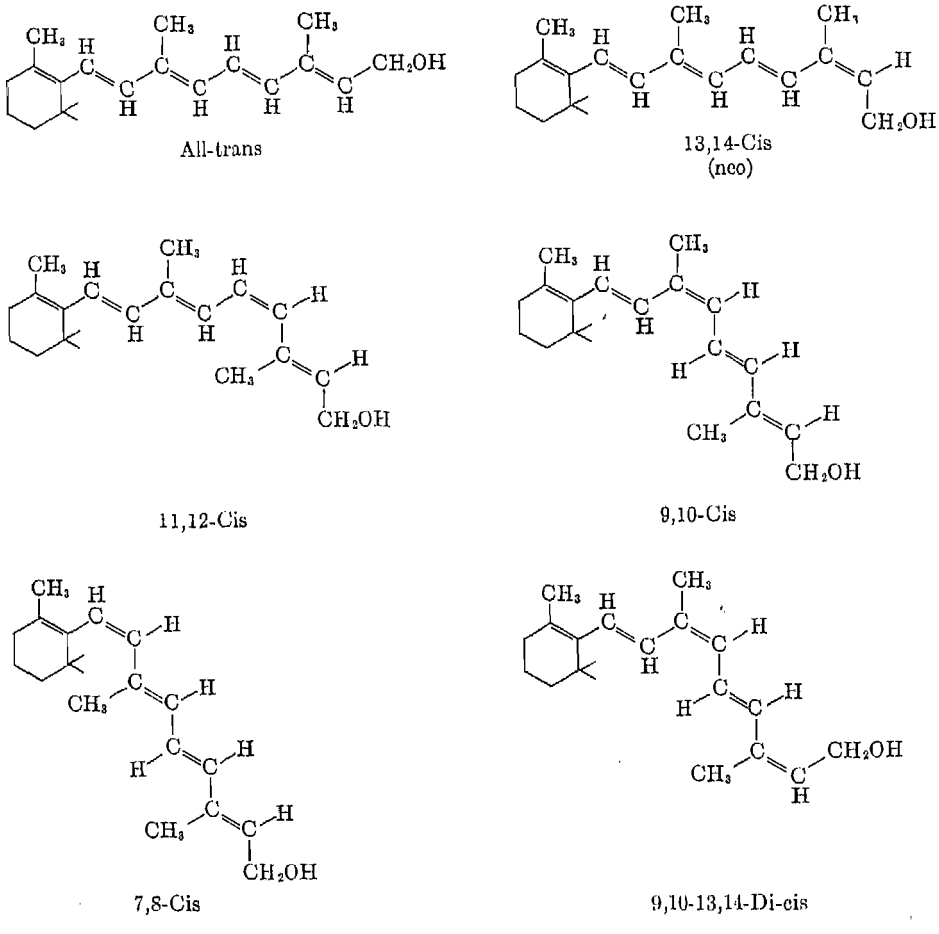


Fig. 3. Stereoisomers of vitamin A.

The effect of one or more cis configurations on the growth-promoting activity of vitamin A and the provitamins A is shown in Table IV. In each of these stereoisomeric sets, the all-trans isomer is the most potent form. Since a cis configuration causes a bending of the molecule, the biological data appear to indicate that an overall straight form is necessary for most efficient utilization of the vitamins and provitamins A. Even the poly-cis compound, pro-γ-carotene, which is as active as all-*trans*-γ-carotene, fits into this generalization, for in this isomer the alternating positive and

TABLE IV. Effect of Steric Configuration on Vitamin A Activity.

Compound	Configuration	Percentage of vitamin A activity per mole
vitamin A	all-trans	100
neovitamin A	13,14-cis	75 (1)
9,10-*cis*-vitamin A	9,10-cis	23 (1)
9,10-13,14-di-*cis*-vitamin A	9,10-13,14-di-cis	23 (1)
7,8-*cis*-vitamin A	7,8-cis	23 (1)
11,12-*cis*-vitamin A	11,12-cis	< 3 (55)
retinene	all-trans	91 (1)
neoretinene	13,14-cis	91 (1)
9,10-*cis*-retinene	9,10-cis	19 (1)
9,10-13,14-di-*cis*-retinene	9,10-13,14-di-cis	17 (1)
neoretinene b	7,8-cis	47 (1)
α-carotene	all-trans	53 (72)
neo-α-carotene U	9,10 (or 9′,10′)-cis	13 (72)
neo-α-carotene B	9,10-15,15′ (or 13′,14′)-di-cis	16 (72)
β-carotene	all-trans	100
neo-β-carotene U	9,10-mono-cis	38 (72)
neo-β-carotene B	9,10-15,15′ (or 13′,14′)-di-cis	53 (72)
15,15′-*cis*-β-carotene	15,15′-mono-cis	50 (73)
11,12-11′,12′-di-*cis*-β-carotene	11,12-11′,12′-di-cis	20 (22)
γ-carotene	all-trans	42 (72)
neo-γ-carotene P	9,10-mono-cis	19 (72)
pro-γ-carotene	poly-cis	44 (72)
cryptoxanthin	all-trans	57 (72)
neocryptoxanthin U	9,10-mono-cis	27 (72)
neocryptoxanthin A	15,15′-mono-cis	42 (72)

negative bends of the five type II cis configurations actually serve to cancel each other out to produce an overall straight rod-shaped molecule (72).

In the visual process, the stereochemical requirements are entirely different. Here the all-trans isomer is completely inactive and only the sterically hindered cis isomer, 7,8-*cis*-vitamin A, appears to be the functioning form (see "Biological action and uses").

It has not yet been determined whether the cis isomers of vitamin A and of the provitamins A function as such in the growth-promoting process, or are first stereoisomerized to the all-trans forms. It is known that the body can interconvert stereoisomers of vitamin A as shown by the appearance of both vitamin A and neovitamin A in the livers of rats maintained on either of the two isomers (57). It has also been demonstrated that the body derives the 7,8-*cis*-vitamin A used in vision from the all-trans isomer (67).

Standards

In 1949 the Committee on Biological Standardization of the World Health Organization redefined the International Unit (I.U.) of **vitamin A** as the biological activity of 0.344 γ of vitamin A acetate (70). This is equivalent to 0.300 γ of the free alcohol. Thus 1 gram of vitamin A contains 3.33×10^6 I.U.

The international reference standard consists of a cottonseed oil solution containing 0.344 γ of vitamin A acetate per 0.1 mg. of solution stabilized with a minimum of 0.1% of tocopherol. The U.S.P. reference standard (65) adopted in 1948 is equivalent to the international standard. The U.S.P. and International units are also equivalent.

The International Unit of **provitamin A** activity is defined as the biological activity of 0.600 γ of pure all-*trans*-β-carotene (56). Thus 1 gram of β-carotene contains 1.67×10^6 I.U. of provitamin A. Biologically one unit of vitamin A is equivalent to one unit of provitamin A. The international provitamin A reference standard consists of a cottonseed oil solution of pure β-carotene containing 0.600 γ per 5.00 mg. of solution stabilized with hydroquinone (56). Up until the adoption of the present vitamin A acetate standard, the U.S.P. used the international β-carotene standard to calibrate cod-liver oils as vitamin A reference standards.

A very thorough review of this subject has been written by Morton (49).

Assay

VITAMIN A

The assay of vitamin A can be accomplished by any one of three accepted methods: biological, colorimetric or spectrophotometric.

Biological Methods. The original assay procedure, still widely used, is based on the biological *response of vitamin A-deficient rats* (64). The method lacks specificity in that it measures not only the vitamin A present but the provitamins as well. Rats are fed on a vitamin A-free diet until they show a cessation of growth. One group is then separated and its diet supplemented by a predetermined dose of standard vitamin A. For a more accurate assay two or three groups on different levels of the standard may be used. The others are divided further into two or more groups and fed different levels of the sample being tested. The rate of growth (that is, increase in body weight) is the criterion of response officially used. At the end of 4 weeks, the assay is terminated, and the increase in weight of the animals fed the unknown sample is compared with that of the standard group. From these data the vitamin A content of the sample can be calculated. If provitamins are present in the sample, these must be determined separately by other methods and the value obtained subtracted from the bioassay value.

The greatest source of error in this assay is the individual differences in the response of the test animals. Most reliable bioassays are for these reasons best carried out in laboratories routinely performing them.

Guggenheim and Koch (26) have proposed *a liver storage test* for vitamin A which offers a partial solution of the bioassay problem. The basis of the procedure is the well-recognized fact that the amount of vitamin A stored in the liver varies directly with the quantity fed. Weanling rats are placed on a standard vitamin A-free diet for a period of 6 days. The animals are then separated into groups and on two successive days dosed with the vitamin A standard or test sample. Forty-eight hours after the last dose, the livers are removed and analyzed by the Carr-Price procedure.

Compared to the rat-growth assay, the method saves labor, time, and cost. Furthermore, there is excellent agreement between the values obtained by the two procedures (20). The chief limitation of the liver storage test lies in the shortcomings of the Carr-Price assay.

Colorimetric Method (Carr-Price) (2). The colorimetric assay for vitamin A is based on the Carr-Price reaction. The intensity of the blue color, $\lambda_{max.}$ 620 mμ ("blue value"), formed when vitamin A and antimony trichloride are mixed in chloroform solution is measured and compared to that given by a standard solution of vitamin A. This assay is subject to a number of serious sources of error, chief among which is the speed with which the color develops and fades, making time a vital parameter in the procedure. In addition small amounts of moisture or unsaturated substances hamper the formation of the blue color or produce interfering colors. Nevertheless, with experience and adequate provision for these factors, accurate and reproducible assays of vitamin A can be made by this method. One of its advantages that gives it wider applicability over the bioassay and spectrophotometric assays, is its specificity for vitamin A. The U.S.P. relies upon it as an identification test for vitamin A to be carried out in conjunction with the spectrophotometric assay (64a).

Spectrophotometric Method (2,64a). The characteristic ultraviolet absorption spectrum of vitamin A affords the most accurate and reproducible means of estimating the vitamin. The extinction at 325 mμ compared to that of a standard sample gives the vitamin A content directly. This method is applicable to solutions of the pure (or nearly pure) vitamin. Errors due to other materials absorbing in the region 300–350 mμ can be corrected by a procedure developed by Morton and Stubbs (49). This comprises measuring the absorption at 310 and 334 mμ as well as at 325 mμ, and thereby estimating the amount by which the shape of the absorption curve obtained differs from that of pure vitamin A. When the correction is too large, however, separation of the vitamin A from the extraneous absorbing material is necessary prior to assay.

PROVITAMIN A CAROTENOIDS

These carotenoids can be assayed biologically, by the solvent partition method, or by chromatography (2). The Carr-Price assay is not applicable to the provitamin A carotenoids, since they all give different colors with this reagent. The laborious nature of the bioassay and the nonspecificity of the solvent partition method have made chromatography the method of choice. With a 1:3 mixture of magnesia and diatomaceous earth (Celite or Super-Cel) as adsorbent and a 2–5% solution of acetone in petroleum ether as eluent, the separation of the carotenes from other carotenoids and extraneous materials can be rapidly and accurately accomplished. The eluted carotenes are then determined spectrophotometrically.

VITAMIN A AND CAROTENE

The determination of vitamin A and carotene in the presence of each other is frequently necessary in such products as butter, milk, and eggs, and, clinically, in blood serum. A Carr-Price determination is first made for the vitamin A on an ether extract of the material. The carotene is then chromatographically separated from another aliquot of the ether extract and determined spectrophotometrically.

Biological Action and Uses (45,46,67,69)

Vitamin A deficiency in humans is not associated with any clear-cut clinical syndrome as in the case of many other vitamins like thiamine (*q.v.*) (beriberi), nicotinic acid (*q.v.*) (pellagra), ascorbic acid (*q.v.*) (scurvy), or vitamin D (rickets). In experi-

mental animals, the lack of vitamin A causes a distinct cessation of growth (nonskeletal), the appearance of xerophthalmia, and cornification of many epithelia such as those of the respiratory, digestive, urinary, and vaginal tracts. Accompanying manifestations may be susceptibility to infections, nephrolithiasis, and degenerative changes in spinal and cranial nerves.

In man, extreme cases of vitamin A deficiency are very rare, for the adult human appears to have an enormous capacity to store and utilize vitamin A previously acquired. Symptoms that have been clinically associated with vitamin A deficiency are xerophthalmia, follicular hyperkeratosis, cutaneous xerosis, and night blindness. Decreased resistance to infection is also encountered.

The preponderant part of the vitamin A ingested by animals is stored in the liver, essentially in the esterified form, and the body draws upon this reservoir for its needs. In the blood stream it is found largely in unesterified form. Absorbed carotene is converted into vitamin A; according to prevailing theory, this occurs in the walls of the small intestines. The extent of conversion varies greatly with species. The rat is the best convertor and the cow a relatively poor one. Considerable quantities of carotene are consequently found in the liver, fat depots, and milk of cows.

The mechanisms involved in the *in vivo* conversion of the provitamins A to vitamin A are not yet understood. This subject has been discussed in detail by Goodwin (25) and Zechmeister (72).

TABLE V. Recommended Daily Intake of Vitamin A.[a]

Group	Age, yr.	I.U.
Men	25–65	5,000
Women	25–65	5,000
	Pregnant (3rd trimester)	6,000
	Lactating (850 ml. daily)	8,000
Infants	0–1	1,500
Children (either sex)	1–3	2,000
	4–6	2,500
	7–9	3,500
	10–12	4,500
	13–20	5,000

[a] For people in normal health living in a temperate climate.
Source: Food and Nutrition Board of the National Research Council (U.S.) 1953.

The only physiological function in which the role of vitamin A is relatively well understood is that of vision. This has been clarified largely through the efforts of G. Wald. The retinas of most vertebrates contain two types of light receptors: rods for vision in dim light, and cones for vision in bright light. The former contain the light-sensitive pigment *rhodopsin* and the latter *iodopsin*. Chemically, rhodopsin is the conjugate of retinene (vitamin A aldehyde) with the protein opsin. Iodopsin is a similar compound which differs only in the protein moiety. On exposure to light rhodopsin breaks down (bleaches) into all-*trans*-retinene and opsin. For the resynthesis of rhodopsin in the retina, only 7,8-*cis*-retinene can be used. The source of this isomer of retinene is vitamin A. It is assumed that in the retina vitamin A, all-*trans*-retinene, and the corresponding 7,8-cis isomers are in equilibrium with each other, the stereoisomerization being brought about through action of light and enzymes, and the oxida-

tion-reduction by a specific dehydrogenase. In fresh-water fish, an analogous process presumably takes place with vitamin A_2 and the corresponding aldehyde, retinene$_2$. The conjugate of opsin and retinene$_2$ is called *porphyropsin*.

Toxic effects in man from an overdosage of vitamin A are extremely rare. Polar bear liver, which has the highest concentration of vitamin A to be found in any animal organ, is known to be toxic. Animals continuously receiving large doses of concentrated liver oils have been reported to show loss of hair, multiple fractures, paralysis, and fatty degeneration of the liver.

The recommended daily intake of Vitamin A for humans is shown in Table V.

The use of vitamin A is now well established in the pharmaceutical, food fortification, and animal food industries. Before the advent of the synthetic product, it had only limited use in food fortification because of the objectionable odor and taste of fish-liver oil concentrates. This was somewhat alleviated by molecular distillation, which removed the fishy odor and taste but on the other hand increased the cost of the product. Today, with the tasteless and odorless synthetic product, there is an ever-increasing trend toward incorporating vitamin A in various processed foods and food concentrates. In the animal feed industries, liver oils still continue in wide use because of the acceptability there of low-potency and hence low-cost oils. Also, taste and odor are not vital factors in animal foods. In the pharmaceutical industry the synthetic product is used almost exclusively.

Relationship of Structure to Vitamin A Activity. Vinylogous derivatives of vitamin A have been obtained by the oxidation of β-carotene. Under controlled conditions the opening of one of its rings can be effected at the 5′,6′-position to yield semi-β-carotenone (XXIII; R being $=CHCOC(CH_3)_2(CH_2)_3COCH_3$) (40). This is biologically active. Further oxidative degradation of the side chain yields β-apo-2-carotenal (β-8′-apocarotenal) (XXIII; R being $=O$) (40) and β-apo-4-carotenal (β-12′-apocarotenal) (40), the corresponding aldehyde with one less isoprene unit. Both of these aldehydes are very potent biologically, as are their corresponding alcohols. The next member of this series, one isoprene unit down, would be vitamin A aldehyde (retinene, β-15-apocarotenal). It is as potent as vitamin A in the rat growth assay (1). Its oxidation product, vitamin A acid, has only about half the potency of vitamin A (13).

The two possible acetylenic analogs of vitamin A are known, the 7,8 (3) and the 11,12 (55). These show, respectively, 40% and 15% the potency of vitamin A. Introduction of a 7,8-acetylene group in vitamin A acid causes a fivefold drop in activity (3).

A shift of the ring double bond (*α-vitamin A* and its methyl ether) (51,59) causes a hundredfold drop in activity, while a shift of all five double bonds one carbon back toward the ring (*retrovitamin A* and its methyl ether) (51a,52) causes complete loss of activity. Epoxidation of one of the double bonds (position unknown) removes most of the activity (39).

Omission or change of position of a side-chain methyl group in vitamin A results in complete loss of activity (8), as does replacement of the cyclohexenyl ring with a phenyl group (68).

On replacing the hydroxyl with a dimethylamino (48) or hydroxymethyl (48) group (*homovitamin A*), considerable activity is still retained. Authentic vitamin A hydrocarbon has not yet been biologically assayed (54).

The esters of vitamin A show the same activity as the alcohol on a molar basis.

This also holds true for the methyl ether, but the butyl and phenyl ethers are less active (35).

Except for retinene, no variant of vitamin A showing equivalent activity has yet been obtained.

Bibliography

(1) Ames, S. R., Swanson, W. J., and Harris, P. L., *Abstracts 126th Meeting A.C.S.* (New York), 36C, Sept., **1954**; *J. Am. Chem. Soc.*, in press.
(2) Association of Vitamin Chemists, *Methods of Vitamin Assay*, 2nd ed., Interscience, N.Y.-London, 1951.
(3) Attenburrow, J., Cameron, A. F. B., Chapman, J. H., Evans, R. M., Hems, B. A., Jansen, A. B. A., and Walker, T., *J. Chem. Soc.*, **1952**, 1094.
(4) Ball, S., Goodwin, T. W., and Morton, R. A., *Biochem. J.*, **42**, 516 (1948).
(5) Baxter, J. G., *Fortschr. Chemie org. Naturstoffe*, **9**, 41 (1952).
(6) Baxter, J. G., and Robeson, C. D., *J. Am. Chem. Soc.*, **64**, 2407, 2411 (1942).
(7) Campbell, K. N., and Campbell, B. K., *Chem. Revs.*, **31**, 148 (1942).
(8) Cheeseman, G. W. H., Heilbron, I. M., Jones, E. R. H., Sondheimer, F., and Weedon, B. C. L., *J. Chem. Soc.*, **1949**, 1516.
(9) *Chem. Eng. News*, **29**, 1316 (1951).
(10) Committee on Biochemical Nomenclature of the National Research Council, "Nomenclature of Carotenoid Pigments," *Chem. Eng. News*, **24**, 1235 (1946).
(11) Deuel, H. J., Jr., *The Lipids*, Vol. I, Interscience, N.Y.-London, 1951, chs. VI, VII.
(12) Dieterle, J. M., and Robeson, C. D., *Science*, **120**, 219 (1954).
(13) Dorp, D. A. van, and Arens, J. F., *Rec. trav. chim.*, **65**, 338 (1946).
(14) Edisbury, J. R., Morton, R. A., and Simpkins, G. W., *Nature*, **140**, 234 (1937).
(15) Embree, N. D., and Shantz, E. M., *J. Am. Chem. Soc.*, **65**, 906 (1943).
(16) Eugster, C. H., Garbers, C. F., and Karrer, P., *Helv. Chim. Acta*, **36**, 1378 (1953).
(17) Euler, H. von, Günther, G., Malmberg, M., and Karrer, P., *Helv. Chim. Acta*, **21**, 1619 (1938).
(18) Farrar, K. R., Hamlet, J. C., Henbest, H. B., and Jones, E. R. H., *J. Chem. Soc.*, **1952**, 2657.
(19) *Food and Agr. Organization, U.N.*, FAO Nutritional Studies No. 11, Rome, March 1954.
(20) Foy, J. R., and Morgareidge, K., *Anal. Chem.*, **20**, 304 (1948).
(21) Garbers, C. F., Eugster, C. H., and Karrer, P., *Helv. Chim. Acta*, **35**, 1850 (1952).
(22) Garbers, C. F., Eugster, C. H., and Karrer, P., *Helv. Chim. Acta*, **37**, 382 (1954).
(23) Gillam, A. E., Heilbron, I. M., Lederer, E., and Rosanova, V., *Nature*, **140**, 233 (1937).
(24) Glover, J., Goodwin, T. W., and Morton, R. A., *Biochem. J.*, **43**, 109 (1948).
(25) Goodwin, T. W., *The Comparative Biochemistry of the Carotenoids*, Chapman and Hall, London, 1952.
(26) Guggenheim, K., and Koch, W., *Biochem. J.*, **38**, 256 (1944).
(27) Heilbron, I. M., Johnson, A. W., Jones, E. R. H., and Spinks, A., *J. Chem. Soc.*, **1942**, 727.
(28) Heilbron, I. M., Jones, W. E., and Bacharach, A. L., *Vitamins and Hormones*, **2**, 155 (1944).
(29) Henbest, H. B., Jones, E. R. H., Owen, L. N., and Thaller, V., *J. Chem. Soc.*, in press.
(30) Hickman, K. C. D., *Ind. Eng. Chem.*, **29**, 968, 1107 (1937).
(31) Holmes, H. N., and Corbet, R. E., *J. Am. Chem. Soc.*, **59**, 2042 (1937).
(32) Hubbard, R., and Wald, G., *J. Gen. Physiol.*, **36**, 269 (1952).
(33) Inhoffen, H. H., and Siemer, H., *Fortschr. Chemie org. Naturstoffe*, **9**, 1 (1952).
(34) Isler, O., Huber, W., Ronco, A., Kofler, M., *Helv. Chim. Acta*, **30**, 1911 (1947).
(35) Isler, O., Ronco, A., Guex, W., Hindley, N. C., Huber, W., Dialer, K., Kofler, M., *Helv. Chim. Acta*, **32**, 489 (1949).
(36) I.U.P.A.C. (15th Conf.), "Rules of Nomenclature of the Carotenoids," *J. Chem. Soc.*, **1951**, 3525.
(37) Jansen, B. C. P., *Bull. soc. sci. hyg. aliment.*, **38**, 127 (1950).
(38) Karrer, P., and Eugster, C. H., *Helv. Chim. Acta*, **33**, 1172 (1950).
(39) Karrer, P., and Jucker, E., *Helv. Chim. Acta*, **30**, 559 (1947).
(40) Karrer, P., and Jucker, E. (trans. and rev. by E. Braude), *Carotenoids*, Elsevier, Amsterdam, 1950.
(41) Karrer, P., and Morf, R., *Helv. Chim. Acta*, **16**, 625 (1933).
(42) Karrer, P., Morf, R., and Schopp, K., *Helv. Chim. Acta*, **14**, 1033, 1431 (1931).

(43) Koehn, C. J., *Arch. Biochem.*, **17**, 337 (1948).
(44) Kuhn, R., and Morris, C., *Ber.*, **70B**, 853 (1937).
(45) Mason, K. E., in Sebrell and Harris, *The Vitamins*, Academic Press, N.Y., 1954, Vol. I, pp. 137, 171.
(46) Mattson, F. H., in Sebrell and Harris (see ref. 45), Vol. I, p. 163.
(47) Meunier, P., Dulou, R., and Vinet, A., *Bull. soc. chim. biol.*, **25**, 371 (1943).
(48) Milas, N. A., *Vitamins and Hormones*, **5**, 1 (1947).
(49) Morton, R. A., *J. Pharm. and Pharmacol.*, **2**, 129 (1950).
(50) N.N.R., 1954, p. 546.
(51) Oroshnik, W., *J. Am. Chem. Soc.*, **76**, 5499 (1954).
(51a) Oroshnik, W., unpublished work.
(52) Oroshnik, W., Karmas, G., and Mebane, A. D., *J. Am. Chem. Soc.*, **74**, 295 (1952).
(53) Oroshnik, W., and Mebane, A. D., *J. Am. Chem. Soc.*, **76**, 5719 (1954).
(54) Oroshnik, W., Mebane, A. D., and Karmas, G., *J. Am. Chem. Soc.*, **75**, 1050 (1953).
(55) Oroshnik, W., and Wald, G., *Abstracts 14th International Congress of I.U.P.A.C.* (Zurich) July, 1955.
(56) *Quart. Bull. Health Organisation League Nations*, **3**, 428 (1934).
(57) Robeson, C. D., and Baxter, J. G., *J. Am. Chem. Soc.*, **69**, 136 (1947).
(58) Robeson, C. D., Blum, W. P., Dieterle, J. M., Cawley, J. D., and Baxter, J. G., *Abstracts 126th Meeting A.C.S.* (New York), 34C (Sept., 1954); *J. Am. Chem. Soc.*, in press.
(59) Robeson, C. D., Cawley, J. D., Weisler, L., Stern, M. H., Eddinger, C. C., and Chechak, A. J., *Abstracts 126th Meeting A. C. S.* (New York), 34C (Sept. 1954); *J. Am. Chem. Soc.*, in press.
(60) Rosenberg, H. R., *Chemistry and Physiology of the Vitamins*, rev. reprint, Interscience, N.Y.-London, 1945.
(61) Shantz, E. M., *Science*, **108**, 417 (1948).
(62) Shantz, E. M., and Brinkman, J. H., *J. Biol. Chem.*, **183**, 467 (1950).
(63) Shantz, E. M., Cawley, J. D., and Embree, N. D., *J. Am. Chem. Soc.*, **65**, 901 (1943).
(64) U.S.P. XIV, 1950.
(64a) U.S.P. XV, 1955.
(65) U.S.P. Reference Standards, April 1951.
(66) Wald, G., *Nature*, **139**, 1017 (1937).
(67) Wald, G., in Sebrell and Harris, *The Vitamins*, Academic Press, N.Y., 1954, Vol. I, p. 59.
(68) Weedon, B. C. L., and Woods, R. J., *J. Chem. Soc.*, **1951**, 2687.
(69) Wolbach, S. B., in Sebrell and Harris, *The Vitamins*, Academic Press, N.Y., 1954, Vol. I, p. 106.
(70) *World Health Organization Tech. Rept. Ser.*, **30**, 1 (1950).
(71) Zechmeister, L., *Chem. Revs.*, **34**, 267 (1944).
(72) Zechmeister, L., *Vitamins and Hormones*, **7**, 57 (1949).
(73) Zechmeister, L., Deuel, H. J., Inhoffen, H. H., Leemann, J., Greenberg, S. M., and Ganguly, J., *Arch. Biochem. Biophys.*, **36**, 80 (1952).
(74) U.S. Pat. 2,417,299 (Mar. 11, 1947), L. Freedman and E. Green (to U.S. Vitamin Corp.).
(75) U.S. Pat. 2,451,739 (Oct. 19, 1948), O. Isler (to Hoffmann-LaRoche).
(76) U.S. Pat. 2,451,740 (Oct. 19, 1948), H. Lindlar (to Hoffmann-LaRoche).
(77) U.S. Pat. 2,518,230 (Aug. 8, 1950), L. Freedman and E. Green (to U.S. Vitamin Corp.).
(78) U.S. Pat. 2,610,207 (Sept. 9, 1952), H. Lindlar and R. Rügg (to Hoffmann-LaRoche).
(79) U.S. Pat. 2,610,208 (Sept. 9, 1952), J. D. Surmatis (to Hoffmann-LaRoche).

WILLIAM OROSHNIK

VITAMIN B_{12}

Vitamin B_{12} (cyanocobalamin, U.S.P. XV, N.N.R., animal protein factor, LLD factor, antipernicious anemia factor, extrinsic factor) is a red crystalline cyano cobalt complex with a molecular weight of about 1350. Only part of its structure is known.

It is required for normal blood formation, for certain other fundamental metabolic processes, for neural function, and for human and animal growth and maintenance. Human requirements are extremely small—less than a thousandth as great as those for most of the other B vitamins.

With the discovery in 1926 that pernicious anemia could be controlled by the administration of whole liver (42), efforts were begun to obtain the active principle in

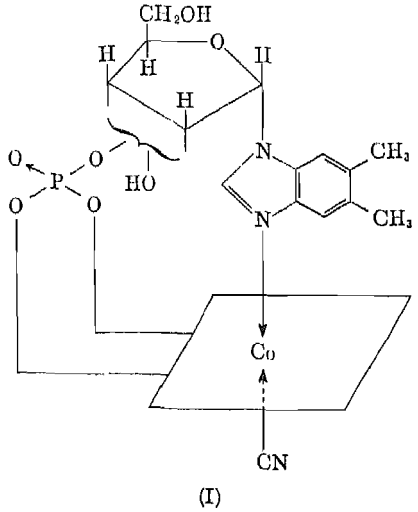
pure form. These efforts involved many groups of investigators and during the next twenty years some advances were made, but progress was very slow. This was partly because of the extremely small amounts of active material present in liver, the only source known at the time; but more particularly because the only guide to fractionation was testing in pernicious anemia patients in relapse, who were very scarce. An extensive review of the purification work before 1945 has been published (56). The discovery of a microbiological assay with *Lactobacillus lactis* (53) for the antipernicious anemia factor gave a criterion for determination of the potency of concentrates and allowed more rapid evaluation of advances made toward isolation. In 1948 Folkers and co-workers announced the isolation of pure crystalline vitamin B_{12} from liver (47), and also the discovery that it could be produced by fermentations (48,65), thus affording a practical large-scale source of the vitamin both as active concentrates and as the pure compound.

Shortly thereafter the isolation of crystalline material was also reported by other groups (20,45,55). Only four months after its isolation was announced, crystalline vitamin B_{12} was made available for therapeutic purposes, and within a year was on the market.

It was further demonstrated that vitamin B_{12} is present in a wide variety of animal tissues, and it soon became evident that many other research efforts directed toward isolation of new animal growth factors, etc., were actually concerned with vitamin B_{12}. However, assumption of too great a specificity of the *L. lactis* assay led to erroneous conclusions, and it is now known that some of the reported vitamin B_{12} activity of natural materials is due to other substances.

STRUCTURE

The empirical composition of vitamin B_{12} is best represented at present by $C_{61-64}H_{89-92}CoN_{14}O_{13-14}P$. Analytical data support several specific formulas, but since the molecule is so large exact knowledge of its structure will be necessary to distinguish



(I)

the correct one. The portion of the molecule whose structure is known is shown in formula (I).

The point of attachment of the phosphate group to the ribofuranose ring is not

known with certainty, and the possibility that it may be present as a cyclic 2′,3′-phosphate cannot be definitely excluded. 5,6-Dimethylbenzimidazole, 1-α-D-ribofuranosyl-5,6-dimethylbenzimidazole (*α-ribazole*) and its 2′- or 3′-phosphate ester (*α-ribazole phosphate*) were isolated early in the structure work (11,12). The α-configuration is unusual since most natural products of this type occur in the β-configuration. Comparison of some of the properties of α-ribazole phosphate with the adenosine 2′- and 3′-phosphates (adenylic acid; see *Nucleic acids*, Vol. **9**, p. 509) of known structure indicates that α-ribazole 3′-phosphate is the correct structure.

In addition to the moieties shown, it is known that vitamin B_{12} contains at least one molecule of D-1-amino-2-propanol (17,61) and at least three and probably more carboxamide groups (3). Analogy with other natural products suggests that the aminopropanol may be a link between the phosphate group and the major portion of the molecule, but definite evidence for or against this structure has not been reported.

The cyano group is bound coordinately to the cobalt, and compounds in which this group has been replaced by other ions are known. Spectral studies have shown quite conclusively that the N(3) of the benzimidazole is also coordinated to the cobalt (5).

The portion of vitamin B_{12} exclusive of the cyano group has been named *cobalamin*, and the names of the derivatives are formed by means of prefixes, as with other metal coordination complexes; for example, cyanocobalamin, hydroxocobalamin.

Because of its physiological action in blood formation and its metal complex nature, a polypyrrole or porphyrin structure (see Vol. **11**, p. 351) was suspected for the basic portion of the vitamin B_{12} molecule, but chemical behavior failed to establish this. However, pyrrole-containing products have been obtained by alkali fusion, and x-ray studies have indicated the presence of four five-membered rings probably connected in a cyclic structure (10). The isolation of two succinimides (3,3-dimethyl-2,5-dioxopyrrolidine-4-propionic acid and the lactone of the corresponding 4-hydroxy acid) as products of oxidative degradation (41) has established the heterocyclic nature of at least part of these rings. Thus it appears likely that, while the structure is not a true polypyrrole or porphyrin, it may be of a similar nature.

Several small degradation products are known, and it has been suggested that a terpene structure is involved (51).

Extensive reviews of the chemistry and structure of vitamin B_{12} have been published (22,52).

PHYSICAL AND CHEMICAL PROPERTIES (22)

Vitamin B_{12} forms red crystals which do not melt below 300°C., but darken to black at about 210–220°; refractive indexes: α, 1.616; β, 1.652; and γ, 1.664. The crystals normally contain about 12% moisture and are soluble in water to the extent of 1.25% at 25°C. Vitamin B_{12} is soluble in alcohols and phenols, but insoluble in acetone, chloroform, and ether.

Aqueous solutions show absorption maxima at 278 ($E^{1\%}_{1\,cm.}$ 115), 361 ($E^{1\%}_{1\,cm.}$ 204), and 550 ($E^{1\%}_{1\,cm.}$ 63) mμ, which are practically independent of pH. The optical activity in aqueous solution is $[\alpha]^{23}_{6563} = -59° \pm 9°$ and $[\alpha]^{20}_{6438} = -110° \pm 10°$.

Aqueous solutions are neutral, but in anhydrous acetic acid vitamin B_{12} is shown by electrometric titration to be a polyfunctional base, and a hexaperchlorate may be crystallized from anhydrous perchloric acid (1). If the presence of one ionizing

group in aqueous solutions is assumed, the molar conductivity is 53. Its electrophoretic mobility in 0.5 *N* acetic acid containing 0.01% potassium cyanide is zero.

Polarographic studies show a single reductive wave and indicate that the normal valence state of the cobalt is +3 and may be reduced to +2. The crystals are diamagnetic.

Reactions. The cyano group of cyanocobalamin may be replaced with other ions (54). The first such compound to be prepared was *hydroxocobalamin* (38), which was made by hydrogenating cyanocobalamin in the presence of a platinum catalyst and then reoxidizing with air. During this process, the cobalt is reduced from a valence state of +3 to +2, freeing the cyanide ion, and subsequently reoxidized taking up a hydroxyl ion to give hydroxocobalamin, or a water molecule to give the aquocobalamin ion, depending on pH and concentration. Illuminated solutions of cyanocobalamin release hydrogen cyanide to a small extent (59), and if this is removed by aeration, the remaining product is hydroxocobalamin. Reaction of hydroxo- or aquocobalamins with acids yields cobalamins containing anions of the acid used. All of these cobalamins are converted to cyanocobalamin by cyanide ions (40).

In cyanide solutions above pH 10 cyanocobalamin is converted into a dicyano complex and then more slowly into a tricyano complex (16).

The other reported chemical reactions of cyanocobalamin involve degradation of the molecule. Dilute acid treatment yields some products which are the result of hydrolysis of only amide groups. Seven of these acids resulting from partial and complete hydrolysis of three amide groups have been isolated and reconverted to cyanocobalamin by preparing mixed anhydrides and treating with ammonia (3).

More vigorous acid hydrolysis frees the nucleotide, α-ribazole phosphate, which may be further degraded to ribazole or 5,6-dimethylbenzimidazole depending on conditions, and usually simultaneous degradation of the remainder of the cyanocobalamin molecule occurs. Brief treatment with concentrated acid removes α-ribazole phosphate with little effect on the remainder of the molecule (28). The product is a red amorphous substance which also has been isolated from calf feces and called *Factor B* (24). It, too, is a cyano complex, but it is not known what groups replace those removed. The compound obtained by removing the aminopropanol from Factor B has also been reported (26).

Vitamin B_{12} is unstable toward both oxidizing and reducing agents, but most of the reaction products have not been identified. Oxalic, succinic, methylsuccinic, and dimethylmalonic acids have been isolated from oxidative degradation experiments (51).

Optimum stability in aqueous solutions is at pH 4.5–5.0. No significant loss of activity occurs at room temperature for periods of 2 years or longer. However, at elevated temperatures or a higher or lower pH decomposition is more rapid.

OCCURRENCE

Vitamin B_{12} occurs in practically all animal products, probably in the form of a protein complex, in larger amounts in those that are rich in protein. Liver, kidney, and some seafoods are the richest sources. Fermented materials such as rumen contents and feces are particularly rich sources, and it is known to be produced by many actinomycetes and other bacteria, but in general not by molds (30). It is possible that it is entirely a product of fermentation and that that found in animal tissues is either ingested or produced by intestinal fermentation.

In general, plant material contains little or no vitamin B_{12}. An exception is algae, and it has been suggested that these plants may be the source of the relatively large amounts of the vitamin found in some shellfish and fish.

Literature reports of the vitamin B_{12} contents of natural materials should in many cases be qualified because of the presence of other substances which could give a response in the particular assay used (see p. 822). This is particularly important in the case of fermentation broths, and in some cases it has been demonstrated that the major portion of the activity measured microbiologically is due to something other than vitamin B_{12} (14).

Table I lists the contents of vitamin B_{12}-active substances of a variety of natural materials (52).

Production of vitamin B_{12} and other vitamin B_{12}-active substances has been shown for microorganisms belonging to the Schizomycetes, *Torula* and *Eremothecium*, including bacteria of the genera *Streptomyces*, *Alcaligenes*, *Bacillus*, *Pseudomonas*, *Mycobacterium*, and *Escherichia* (30,79).

TABLE I. Content of Vitamin B_{12}-Active Substances of Some Natural Materials.

Material	Vitamin B_{12} activity γ/kg. (dry)	Material	Vitamin B_{12} activity γ/kg. (dry)
Milk	3–5 (liter fresh)	Clams	2500
Whole milk powder	10–26	Fish meal	170–1500
Cheese	28	Salmon kidney	18,000
Egg yolk	28	Beef	
Green leafy vegetables	0 or traces	Round	55–79
(celery, pepper, kale,		Liver	500
tomato, cabbage,		Kidney	500
kohlrabi, broccoli,		Heart	250
leek)		Mutton	88
Algae	60–280	Horsemeat	70–75
Filet of sole	13	Chicken meat	52
Oysters	150–2800		

Protein complexes in which vitamin B_{12} is believed to occur in the natural state have been isolated but little is known about them (60).

An extensive review of the sources of vitamin B_{12} has been published (18).

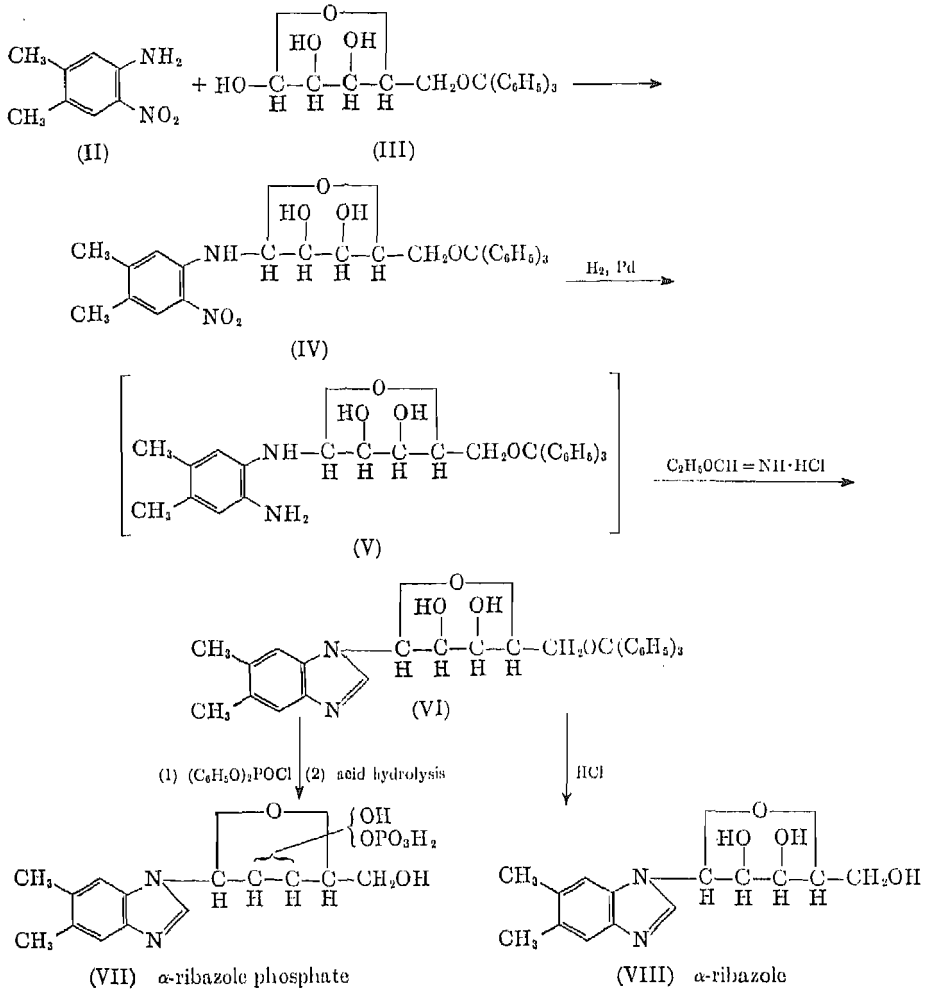
CHEMICAL SYNTHESIS

Chemical synthesis has necessarily been limited to the known α-ribazole phosphate portion of the cobalamin molecule. The reactions outlined in Scheme 1 illustrate syntheses which have been carried out.

Preparation of benzimidazoles is conveniently carried out by starting with the appropriately substituted *o*-nitroaniline (II), reducing to the corresponding diamine, and heating the latter with formic acid or its derivatives. Heating the diamine with acetic acid in hydrochloric acid yields the corresponding 2-methyl compound. A large number of methyl-substituted benzimidazoles were synthesized by these procedures (6) for spectroscopic study during the structure work on vitamin B_{12}.

For preparation of α-ribazole, 2-nitro-4,5-dimethylaniline (II) and 5-*O*-trityl-D-ribofuranose (III) are condensed by boiling with benzene and acetic acid to give 2-nitro-4,5-dimethyl-*N*-(5-*O*-trityl-D-ribofuranosyl)aniline (IV). Hydrogenation in the

SCHEME I



presence of a palladium catalyst is assumed to give the amino riboside (V), and, without isolation, the imidazole ring is closed by heating with an alkyl formimino ether hydrochloride yielding 1-(5-*O*-trityl-α-D-ribofuranosyl)-5,6-dimethylbenzimidazole (VI) (34). Other ring-closing agents which have been used for similar compounds are *N*-(dichloromethyl)formamidine hydrochloride, ethyl formate, and carbon disulfide with barium hydroxide followed by hydrogenation with Raney nickel to remove the 2-mercapto group formed (33).

Acid hydrolysis removes the trityl group from (VI) to give 1-α-D-ribofuranosyl-5,6-dimethylbenzimidazole (α-ribazole) (VIII). The yield is about 6% from the nitro riboside (IV).

Acetylation of the nitro riboside (IV) to the 2,3-diacetyl derivative followed by the reactions shown leads to the β-isomer of ribazole.

The best reported procedure (37) for the synthesis of α-ribazole phosphate involves the reaction of 5′-*O*-trityl-α-ribazole (VI) with diphenyl chlorophosphate. Acid hydrolysis removes the trityl and phenyl groups and α-ribazole phosphate (VII) is

isolated through its lead salt. The product is identical with the degradation product from vitamin B_{12}, but it is not known whether it is the 2′- or 3′-phosphate.

By variations of the reactions outlined above and by reaction of polyacetylglycosyl halides with benzimidazoles or their chloromercuri derivatives, other 1-glycosyl-5,6-dimethylbenzimidazoles have been synthesized including ribopyranosyl, glucopyranosyl, arabinopyranosyl, arabinofuranosyl, and lyxopyranosyl derivatives (33,35).

Numerous other benzimidazole glycosides have been synthesized, and several of them, particularly those containing halogenated benzimidazoles, have a significant inhibitory effect on influenza virus multiplication (57).

BIOSYNTHESIS

On an experimental basis it has been possible to produce vitamin B_{12}, several of its naturally occurring non-cobalamin analogs, and a number of new analogs biosynthetically (23). This is accomplished by the use of mutant strains of microorganisms which require vitamin B_{12} or related compounds but which have lost their ability to synthesize these substances, probably owing to inability to synthesize the Factor B portion of the molecule. By growing such a mutant of *Escherichia coli* in a medium containing Factor B and the appropriate nucleotide (corresponding to ribazole phosphate) or nucleotide base (corresponding to the dimethylbenzimidazole), the new compounds have been produced. Without supplementation with a nucleotide component, Factor B is converted into *Factor C* (24), a compound of unknown structure. For example, supplementation with 5,6-dimethylbenzimidazole, α-ribazole phosphate, or riboflavin gave vitamin B_{12}; adenine gave *pseudovitamin* B_{12}; and 2-methyladenine gave *Factor A* (pseudovitamin B_{12a}). New analogs were produced by supplementation with a number of 4- and 5-substituted benzimidazoles, several purines related to adenine, a benzotriazole and a benzothiazole. The compounds were not isolated in crystalline form, but Factor B labeled with Co^{60} was used, and the production of new substances determined both by the reduction of the amount of Factor C formed and the presence of new spots after paper-strip chromatography. Microbiological activity was measured by assay with *E. coli* and *Ochromonas* (see p. 823).

The analog of vitamin B_{12} containing *benzimidazole* in place of 5,6-dimethylbenzimidazole has been obtained by a slightly different procedure (19,21). A mutant of *Streptomyces griseus* (which normally produces vitamin B_{12}), when grown in the presence of large amounts of *o*-phenylenediamine, produces this new analog at the expense of vitamin B_{12} production. The new substance has been obtained in crystalline form. Addition of relatively small amounts of 4,5-dimethyl-*o*-phenylenediamine to the fermentation prevented formation of the new substance and only vitamin B_{12} was produced.

At present, methods involving supplementation with Factor B are of no value for the production of cobalamins since vitamin B_{12} is much more readily available than Factor B. However, by such biosyntheses new vitamin B_{12} analogs obtainable in no other way have been prepared for biological evaluation.

COMMERCIAL PRODUCTION

Vitamin B_{12} is now produced almost exclusively by fermentation, and its production has become one of the important fermentation industries in the United States. It is generally produced by primary fermentation, but in some instances is obtained from broths used primarily for production of antibiotics. This is largely a matter of

economics, since maximum production of the antibiotic and maximum production of cobalamin generally do not occur under the same fermentation conditions.

Another source is sewage, which is known to contain cobalamin-like compounds in addition to vitamin B_{12}. With one exception (26), the chemical and biological properties of these cobalamin-like compounds are not known. A process for extracting the vitamin B_{12} from sewage has been patented (75), and concentrates containing as much as 40 mg./lb. have been obtained.

Fermentation. Microorganisms that have been reported to be used for commercial production (32) are *Streptomyces griseus*, *S. olivaceus*, and *S. aureofaciens* (in connection with chlortetracycline production; see Vol. **13,** p. 777) and the bacteria *Bacillus megatherium*, *Propionobacterium freudenreichii*, and a mixed fermentation of a *Proteus* sp. and a *Pseudomonas* sp. Discussions of the formation of vitamin B_{12}-active compounds by a number of other organisms have been published.

Fermentations to produce vitamin B_{12} are generally carried out by submerged culture in an aerated and stirred medium. The fermentation time is usually 3–5 days.

The following description is based on a process for the production of vitamin B_{12} by *S. olivaceus* (44) which was developed by the Fermentation Division of the Northern Regional Research Laboratories. Pure cultures must be used because contamination invariably results in very low yields. All equipment must be sterile and transfers carried out aseptically.

Media for the growth of these organisms consist of carbohydrate, proteinaceous material, and a source of cobalt and other salts. A typical medium is:

Distillers' solubles	4.0%
Dextrose	0.5–1%
$CaCO_3$	0.5%
$CoCl_2.6H_2O$	1.5–10 p.p.m.
pH adjusted to about 7 with NaOH	

Most forms of distillers' solubles, soybean meal, yeast, casein, etc., are satisfactory under the proper conditions. Cobalt supplementation is essential for maximum yields of cobalamin, although not necessarily for growth of the organism. This has been shown to be true for organisms tested (31) and is the subject of a patent (68).

In some instances cyanide is added to the medium to aid in converting other cobalamins to vitamin B_{12} (77).

The medium may be made up and sterilized batchwise directly in the fermentor (for example, 1 hr. at 250°F.) or sterilized continuously as the fermentor is charged (for example, 13 min. at 330°F.) by mixing directly with live steam. During sterilization steam is blown into openings, and all transfer lines are kept filled with live steam when not in use to ensure sterility.

Pure cultures of the organisms to be used are maintained on agar slants and are grown first in 100–250 ml. of medium in shake flasks and then in two or three successively larger batches to give the required amount of inoculum culture. Inoculation of the fermentors with about 5% of the volume of medium is satisfactory.

During fermentation the temperature is maintained at about 80°F. Within limits, the rate of growth of the culture, but not the final yield of cobalamin, depends on the rate of agitation and aeration. Too rapid aeration causes excessive foaming, and the optimum rate is about 0.5 volume air/min./volume of medium. The air is sterilized by passing through columns of activated charcoal. Foaming is a serious

problem, particularly at the beginning and end of the fermentation. It is controlled by addition of sterile defoaming agents such as soybean oil, corn oil, lard oil, or silicones as required. In some cases a defoamer is added when the medium is prepared.

During the first 24 hr. of the fermentation the pH falls a few tenths of a unit, the sugar concentration decreases rapidly, and the mixture becomes very thick as a result of mycelium growth and probably also of the formation of viscous materials such as polysaccharides. The concentration of cobalamin in the beer rises very slowly for about 20 hr. and then much more rapidly. After 2–4 days when the available nutrients are consumed, lysis of the mycelium begins, the pH rises to about 8, and the mash becomes quite thin. Little or no additional cobalamin is formed after lysis begins. The mash is then stabilized by reducing the pH to about 5 with sulfuric acid and adding small quantities of a reducing agent such as sodium sulfite.

Yields of cobalamin are usually in the range of 1–2 mg./l. in the final broth. The highest yield reported in the literature is 8 mg./l. (43).

During the major part of the fermentation period, most of the cobalamin is present in the mycelium, but at the end a considerable portion is in solution. Heating the mixture to boiling at pH 5 or below frees the cobalamin quantitatively from the mycelium.

Essentials of the production of cobalamins by other bacterial fermentations are similar to those for *Streptomyces* although there are differences in media, conditions, time, etc., for optimum yields (29).

Work-up of the final broth containing cobalamins is determined by the type of product to be produced.

Production of Vitamin B_{12} Feed Supplements. In order to prepare low-potency concentrates of vitamin B_{12} for use as feed supplements, usually all that is necessary is to evaporate the final fermentation broth to dryness. These final broths contain about 3% solids and are first evaporated *in vacuo* to a solids content of 15–20%, and the resulting sirups are drum-dried or spray-dried. Differences in conditions during this processing do not seriously affect the potency of the product, but evaporating the broth at temperatures not above 180°F., drum-drying such that the exit gases are not above 200°F., and cooling the product as rapidly as possible result in about 10% greater activity (44). The concentrates obtained in this way by cobalt-supplemented fermentation are reported to contain 10–30 mg./lb. of cobalamin (32).

In addition to cobalamins these products may also contain other vitamins, minerals, and antibiotics, depending on the source and method of production (32,71). For use as a feed supplement the composition of the major portion of the solids is important for determining its nutritive value. The product prepared by evaporating whole broth from *Bacillus megatherium* has much the same composition as yeast (*q.v.*) with respect to amino acids and B vitamins (29).

Production of Crystalline Vitamin B_{12} from Fermentation Broths. Processes used commercially for the production of vitamin B_{12} have not been described in detail, and most of the published information is found in the patent literature.

One of the first steps is to treat the filtered broth with cyanide, which converts all the cobalamins into cyanocobalamin (64), although this step may also be carried out after some concentration has been achieved. The cyanocobalamin is next adsorbed from solution. Several substances have been reported for this purpose: charcoal (63), fuller's earth, bentonite (73), and ion-exchange resins (74). Elution from the adsorbent is usually accomplished by the use of an aqueous solution of materials rang-

ing from organic bases to hydrochloric acid. Water, water-acetone, and solutions of sodium cyanide or sodium thiocyanate have been used.

Some type of extraction is usually carried out next, countercurrent distribution between cresol (70), amylphenol (67), or benzyl alcohol (69) and water or single extraction into an organic solvent such as a phenol (78). Precipitation as a copper or zinc cyanide–cyanocobalamin complex has been reported (72).

Another purification step applicable to aqueous concentrates consists in dissolving a zinc salt in the slightly acid solution and then raising the pH to precipitate zinc hydroxide, which removes many impurities (76).

Chromatography on alumina and final crystallizations from methanol-acetone, ethanol-acetone, or acetone-water usually complete the process (65,66).

The only industrial yield figures available are again those reported in patents (23, 66). For example, a yield of 65% from broth to a 5% concentrate is reported in one case, and an overall yield of about 4% of crystalline material in another.

There are product patents on crystalline vitamin B_{12} (65) and vitamin B_{12} concentrates (79).

Production and Prices. Vitamin B_{12} is marketed in bulk in the form of (*1*) crystals, (*2*) solid triturations of the crystals, (*3*) "concentrates" containing approximately 1–3 mg./g. of vitamin B_{12} activity for oral human use (commonly called "oral grade solids"), (*4*) a less pure product containing approximately 0.02 mg./g. for animal feeds. Vitamin preparations for human use are manufactured from the first three forms.

The original price of $12,500 per gram for crystalline vitamin B_{12} has been reduced to $245 (1955). Although it is still the highest-priced organic compound on the open market, in bulk form an average clinical dose for treating anemias costs less than 1 cent.

The following figures of the U.S. Tariff Commission reflect the increase in production and decrease in price:

	Production, lb.	Sales, lb.[a]	Value
1951	84	48	$11,044,000
1952	106	61	5,599,000
1953	387	191	14,270,000

[a] In undiluted or uncompounded form.

Vitamin B_{12} in low concentrations for feed supplementation costs about $40 per gram (1955).

ASSAY

Physical, chemical, biological, microbiological, and radioactive tracer methods have been developed for the determination of vitamin B_{12}. Consideration of the very close similarity of the chemical, physical, and biological properties of vitamin B_{12} and related compounds which may occur naturally with it makes it obvious that the value of any assay depends on the other compounds which may be present. Only quantitative isolation of pure cyanocobalamin or something equivalent to it can give a reliable result in a mixture of unknown composition. However, in many cases sufficient knowledge of the other constituents of the material make simple assays reliable. (Liver concentrates used in the treatment of pernicious anemia were formerly standardized in units (see Vol. **2**, p. 5) but are now standardized in terms of equivalence of their vitamin B_{12} activity with a specified amount of cyanocobalamin.)

Physical Methods. The *ultraviolet absorption spectrum* in aqueous solution may be used for estimation (58). The value of the extinction coefficients at 361 mμ is used.

An assay based on *countercurrent distribution* (C.C.D.) uses benzyl alcohol and water (distribution coefficient 1.2) (15).

Chemical Methods. The *cyanide* may be removed quantitatively from aqueous solutions of vitamin B_{12} by aeration and photolysis at pH 5 or lower. The hydrogen cyanide released is purified by passing through solutions of ceric sulfate, silver sulfate, and sulfuric acid and is finally absorbed in sodium hydroxide solution. The amount of cyanide is determined colorimetrically with chloramine-T and pyrazolone pyridine reagents. This assay may be adapted for the determination of total cobalamins by first treating the sample with excess cyanide, removing the uncombined cyanide by aeration in the dark, and then carrying out the above procedure (8).

5,6-Dimethylbenzimidazole is released quantitatively by acid hydrolysis and is then converted chemically into 4,5-dimethyl-*o*-phenylenediamine. This compound reacts with acetylacetone to form a purple benzodiazepine, which can be determined colorimetrically, or with alloxan to form an alloxazine, which can be determined fluorimetrically (7).

Biological Methods. Assays based on the *growth-promoting effect* of vitamin B_{12} on both chicks and rats fed a diet deficient in this vitamin have been developed (27,50). Precautions must be taken to ensure that the chicks or rats used are sufficiently depleted. Chicks to be used are hatched from eggs laid by hens maintained on a vitamin B_{12}-deficient diet. The mothers of young rats to be used are maintained on vitamin B_{12}-low diets, and sometimes the weanling rats are placed on a depletion diet for a short period before the test starts. Protein sources in the assay diets are of vegetable origin, and desiccated thyroid or iodinated casein is sometimes added to the rat diets (46). Assay periods are 3–4 weeks.

Microbiological Methods. Three different procedures are used for measuring microbial growth due to vitamin B_{12}: (*1*) the *tube method*, in which growth is measured by turbidity or titration of the acid produced; (*2*) the *cup-plate method*, in which the potency of the sample is calculated from the diameter of growth around the sample which is contained in a short section of tubing standing on the agar; (*3*) the pad method, in which a small pad of paper soaked with the sample solutions is placed on the agar and growth zones around it are measured.

Organisms which have been used extensively (52) are *Escherichia coli*, *Lactobacillus lactis* Dorner (LLD), *L. leichmannii* (L.l.), and *Euglena gracilis*. The *L. leichmannii* assay has been adopted as standard by the U.S.P. (58). The *Euglena gracilis* assay appears to be the most specific of the group since it is not sensitive to thymidine and other desoxyribosides as are the lactobacilli, nor to methionine as is *E. coli*. It has the disadvantage of being relatively slow (4–7 days) compared with the others (1–3 days). All these organisms are known to respond to cobalamins or cobalamin analogs in addition to cyanocobalamin.

Studies of the chrysomonad *Ochromonas malhamensis* first indicated that it showed growth response specifically to cobalamins (52), but it was subsequently shown to respond to Factor III and the benzimidazole analog of cobalamin, which are also clinically active. Response to additional biosynthetic analogs which have not yet been tested clinically has also been reported (23).

Radioactive Tracer Method. This assay is at present the most reliable, in general,

unless the absence of all interfering substances is definite (4). It determines only vitamin B_{12} but is applicable to the determination of total cobalamins by first converting them to cyanocobalamin by treatment with sodium nitrite and sodium cyanide. A known amount of pure radioactive cyanocobalamin is then added to the sample and equilibrated with cyanocobalamin present. Addition of zinc acetate to an acid solution of the sample and then precipitation of zinc hydroxide by raising the pH to 8.5 removes many impurities. The material is next extracted into a cresol–carbon tetrachloride mixture, effecting considerable purification. After addition of 1-butanol and more carbon tetrachloride, the sample is extracted back into water and the aqueous solution passed through a column of ion-exchange resin (IRP-400 and IR-120). Only those fractions showing a red color are retained. The concentration and purity of the vitamin B_{12} are determined by magnitude and ratios of absorbancies at 548, 430, and 361 mμ. If desired, a benzyl alcohol–water distribution may be carried out as an additional criterion of purity or to effect further purification, particularly when compounds with absorption spectra similar to B_{12} may be present. From measurement of the radioactivity of the solution of purified cyanocobalamin, the amount present in the original sample is calculated. Samples containing as little as 100 γ in concentrations as low as 0.1 γ/ml. can be assayed.

BIOCHEMICAL FUNCTION AND USES

Vitamin B_{12} is required for normal blood formation, growth, certain other fundamental metabolic processes, and neural function and its maintenance. A tissue deficiency of this vitamin causes *pernicious anemia*, which in its completely developed stages is characterized by macrocytosis, megaloblastic bone marrow, leukopenia, neurological and mental changes, endocrine dysfunction, disturbances in fat metabolism, atrophic gastritis, mucous membrane disorders, and occasionally other disturbances.

A deficiency may result either from a dietary insufficiency of vitamin B_{12} or from inability to use that ingested because of a lack of intrinsic factor, a protein which assists absorption of the small amounts of vitamin B_{12} normally present in the intestine. Parenteral administration of small doses, oral administration of small doses with intrinsic factor, or massive oral doses without intrinsic factor produce rapid remissions of all symptoms of pernicious anemia with few exceptions.

Part of the action of vitamin B_{12} is closely related to folic acid (*q.v.*) which in sufficient amounts produces hematopoietic responses in pernicious anemia equivalent to vitamin B_{12} but does not cause remission of the other manifestations, particularly the neurological complications, which are benefited only by vitamin B_{12}. It has been suggested that administration of folic acid in cases of vitamin B_{12} deficiency may result in rapid depletion of the last small reserve of the vitamin B_{12} in the body, thus causing severe neurological symptoms.

Treatment with vitamin B_{12} is of value in nutritional macrocytic anemia and megaloblastic anemia of infancy, trigeminal neuralgia and diabetic neuritis, sprue and herpes zoster. It has been reported useful in certain skin and liver diseases, and a variety of other diseases in which results are not well defined.

Estimates of the human daily requirement of vitamin B_{12} range from less than 1γ to 5γ per day. Children because of their higher metabolic rate may require several times this amount. It is one of the least toxic of therapeutic agents, and doses of 100 mg./kg. (intraperitoneal) in rats and 10 mg. orally in humans have shown no toxic effects.

Vitamin B_{12} appears to be essential for the growth of all animals and poultry and is responsible for most, if not all, of the activity of the "animal protein factor," a factor or factors which permit(s) growth of animals or chicks on rations containing no animal protein (see *Feeds, animal*, Vol. **6,** p. 311; *Tetracyclines (chlortetracycline)*, Vol. **13,** p. 786). Ruminant animals do not have a dietary requirement for the vitamin because they are capable of synthesizing it in the rumen.

There is evidence to indicate that vitamin B_{12} is involved in carbohydrate and fat metabolism, reduction of sulfides to sulfhydryl (mercapto) compounds, nucleic acid metabolism, protein metabolism, transmethylation, and other one- or two-carbon atom transfers, but no specific enzyme or coenzyme function is known as is the case with most of the other B vitamins.

Since the daily requirement and organ contents of vitamin B_{12} are thousands of times lower than those of most of the other B vitamins, it seems logical to reason that its mechanism of action must be quite different.

Extensive reviews of the biochemical function and clinical and nutritional uses of vitamin B_{12} have been published (36,52,62).

Radioactive Forms

Radioactive forms of vitamin B_{12} are useful for assays and for study of the behavior of the substance in biological systems. Vitamin B_{12} containing Co^{60} is the most extensively used form and is prepared by fermentations to which the radioactive cobalt is added (49). The product has a specific activity of up to 770 microcuries per milligram.

Reaction of hydroxocobalamin with $HC^{14}N$ produces cyanocobalamin labeled with C^{14} in the cyano group (9).

No exchange of Co^{60} or P^{32} in the intact molecule has been accomplished.

Analogs

A number of vitamin B_{12} analogs are known belonging to each of two types of compounds. These are all red crystalline substances. The various types of names used in the literature for many of these analogs are very confusing; for example, the designations Factor A, vitamin B_{12m}, and pseudovitamin B_{12d} have all been used for the same compound.

Cobalamins. These derivatives result from replacing the cyano group of cyanocobalamin with other groups (see p. 816). Some of the cobalamins known are: hydroxo-, thiocyanato-, sulfato-, chloro-, bromo-, cyanato-, and nitrocobalamins (40). Hydroxocobalamin has been isolated from fermentation sources (38). *Nitrocobalamin* (also called *nitritocobalamin*) obtained from fermentation broths was later shown to have been formed by chemical reaction during the isolation process (2). Other cobalamins have been reported, but the compounds were subsequently found to be identical with others already known.

The various cobalamins are distinguished from each other by differences in distribution coefficients, refractive indexes of the crystals, and, to a lesser extent, ultraviolet absorption spectra. Their spectra are all very similar to that of vitamin B_{12}, and there are only small differences in the wave lengths of the maxima and the magnitudes of the extinction coefficients.

Microbiological activities of these cobalamins depend on the conditions of the assay and vary from 30 to 100% of the activity of vitamin B_{12} (39). It is presumed

that unless the cobalamin is present in a form which cannot be utilized by the organism, the activity of any of them is equivalent to that of vitamin B_{12}.

Analogs Containing Different Nucleotides. Analogs containing nucleotide bases other than 5,6-dimethylbenzimidazole are known. Some were isolated from natural sources and others prepared by biosynthesis from Factor B and the appropriate benzimidazole or equivalent compound.

TABLE II.

Designation	Nucleotide base	Activity		
		L. lactis Dorner	*L. leichmannii*	Animal
Vitamin B_{12}	5,6-Dimethylbenzimidazole	+	+	+
Factor B	None	Little	–	–
Pseudovitamin B_{12}	Adenine	+	+	–
Factor A (pseudovitamin B_{12a})	2-Methyladenine		+	–
Factor G	Hypoxanthine		Little	–
Factor H	2-Methylhypoxanthine		Little	–
Factor III	Unknown		+	+
"Desdimethylvitamin B_{12}"	Benzimidazole	+	+	+

With the exception of Factor B those shown in Table II are all crystalline compounds. All were isolated from animal feces and/or produced by fermentation (22,24). Factor III is obtained from sewage (26). Additional red cobalt-containing compounds have been reported, but the nucleotide bases have not been characterized (25).

The relationships between these compounds have been established by chemical degradation, identification of the nucleotide bases, and resynthesis biosynthetically (28) (see also p. 819). Pseudovitamin B_{12} and Factor A have been deaminated chemically to Factors G and H, respectively (13). Factors G and H may not be produced directly by fermentation but may be the result of enzymic deamination.

Most other analogs prepared biosynthetically (23) from still other bases in place of the 5,6-dimethylbenzimidazole of vitamin B_{12} have not been crystallized or characterized as yet (see p. 819).

Differentiation and separation of these substances from each other and from cyanocobalamin are largely dependent on chromatography, electrophoresis, and solvent distribution. Many of the chemical and physical properties of the compounds are very similar, and, as indicated in Table II, microbiological activities in some cases are also similar.

Factor III and the vitamin B_{12} analog containing benzimidazole have been reported to have clinical antipernicious anemia activity (21,26), but there have been no reports on the equivalence with the other biological activities of vitamin B_{12}.

Bibliography

(1) Alicino, J. F., *J. Am. Chem. Soc.*, **73**, 4051 (1951).
(2) Anslow, W. K., Ball, S., Emery, W. B., Fantes, K. H., Smith, E. L., and Walker, A. D., *Chemistry & Industry*, **69**, 574 (1950).
(3) Armitage, J. B., Cannon, J. R., Johnson, A. W., Parker, L. F. J., Smith, E. R., Stafford, W. H., and Todd, A. R., *J. Chem. Soc.*, **1953**, 3849.
(4) Bacher, F. A., Boley, A. E., and Shonk, C. E., *Anal. Chem.*, **26**, 1146 (1954).

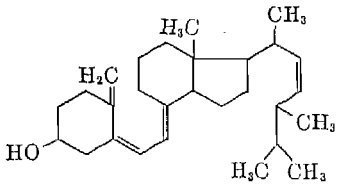
(5) Beavan, G. H., and Holiday, E. R., *J. Pharm. and Pharmacol.*, **4**, 342 (1952).
(6) Beavan, G. H., Holiday, E. R., Johnson, E. A., Ellis, B., Mamalis, P., Petrow, V., and Sturgeon, B., *J. Pharm. and Pharmacol.*, **1**, 957 (1949).
(7) Boxer, G. E., and Rickards, J. C., *Arch. Biochem.*, **29**, 75 (1950).
(8) Boxer, G. E., and Rickards, J. C., *Arch. Biochem. and Biophys.*, **39**, 281 (1952).
(9) Boxer, G. E., and Rickards, J. C., Rosenblum, C., and Woodbury, D. T.. *Arch. Biochem.*, **30**, 470 (1951).
(10) Brink, C., Hodgkin, D. C., Lindsey, J., Pickworth, J., Robertson, J. H., and White, J. C., *Nature*, **174**, 1169 (1954).
(11) Brink, N. G., and Folkers, K., *J. Am. Chem. Soc.*, **72**, 4442 (1950).
(12) Brink, N. G., Holly, F. W., Shunk, C. H., Peel, E. W., Cahill, J. J., and Folkers, K., *J. Am. Chem. Soc.*, **72**, 1866 (1950).
(13) Brown, F. B., Cain, J. C., Gant, D. E., Parker, L. F. J., and Smith, E. L., *Biochem. J.*, **59**, 82 (1953).
(14) Chaiet, L., Miller, T., and Boley, A. E., *J. Agr. Food Chem.*, **2**, 784 (1954).
(15) Chaiet, L., Rosenblum, C., and Woodbury, D. T., *Science*, **111**, 601 (1950).
(16) Conn, J. B., Norman, S. L., and Wartman, T. G., *Science*, **113**, 658 (1951).
(17) Cooley, G., Davies, M. T., Ellis, B , Petrow, V., and Sturgeon, B., *J. Pharm. and Pharmacol.*, **5**, 257 (1953).
(18) Darken, M. A., *Botan. Rev.*, **19**, 99 (1953).
(19) Dulaney, E. L., and Williams, P. L., *Mycologia*, **45**, No. 3, 345 (1953).
(20) Ellis, B., Petrow, V., and Snook, G. F., *J. Pharm. and Pharmacol.*, **1**, 60 (1949).
(21) Fantes, K. H., and O'Callaghan, C. H., *Biochem. J.*, **59**, 79 (1955).
(22) Folkers, K., and Wolf, D. E., *Vitamins and Hormones*, **12**, 1 (1954).
(23) Ford, J. E., Holdsworth, E. S., and Kon, S. H., *Biochem. J.*, **59**, 87 (1955).
(24) Ford, J. E., and Porter, J. W. G., *Brit. J. Nutrition*, **1**, 326 (1953).
(25) Friederich, W., and Bernhauer, K., *Angew. Chem.*, **65**, 627 (1953).
(26) Friederich, W., and Bernhauer, K., *Z. Naturforsch.*, **96**, 686 (1954).
(27) Frost, D. V., Fricke, H. H., and Spruth, H. C., *Proc. Soc. Exptl. Biol. Med.*, **72**, 102 (1949).
(28) Gant, D. E., Smith, E. L., and Parker, L. F. J., *Biochem. J.*, **56**, xxxiv (1954).
(29) Garibaldi, J. A., Ijechi, K., Snell, N. S., and Lewis, J. C., *Ind. Eng. Chem.*, **45**, 838 (1953).
(30) Hall, H. H., Benjamen, J. C., Bricker, H. M., Gill, R. J., Haynes, W. C., and Tsuchiya, H. M., *Bacteriological Proceedings, 50th Meeting, Soc. Am. Bacteriologists* (Baltimore), 1950.
(31) Hendlin, D. H., and Ruger, M., *Science*, **111**, 542 (1950).
(32) Hester, A. S., and Ward, G. E., *Ind. Eng. Chem.*, **46**, 238 (1954).
(33) Heyl, D., Chase, E., Shunk, C. H., Moore, M. U., Emerson, G. A., and Folkers, K., *J. Am. Chem. Soc.*, **76**, 1355 (1954).
(34) Holly, F. W., Shunk, C. H., Peel, E. W., Cahill, J., Lavigne, J. B., and Folkers, K., *J. Am. Chem. Soc.*, **74**, 4521 (1952).
(35) Johnson, A. W., Miller, G. W., Mills, J. A., and Todd, A. R., *J. Chem. Soc.*, **1953**, 3061.
(36) Jukes, T. H., and Stokstad, E. L. R., *Vitamins and Hormones*, **9**, 1 (1951).
(37) Kaczka, E. A., Heyl, D., Jones, W. H., and Folkers, K., *J. Am. Chem. Soc.*, **74**, 5549 (1952).
(38) Kaczka, E. A., Wolf, D. E., and Folkers, K., *J. Am. Chem. Soc.*, **71**, 1514 (1949).
(39) Kaczka, E. A., Wolf, D. E., and Folkers, K., *Science*, **112**, 354 (1950).
(40) Kaczka, E. A., Wolf, D. E., Kuehl, F. A., and Folkers, K., *J. Am. Chem. Soc.*, **73**, 3569 (1951).
(41) Kuehl, F. A., Shunk, C. H., and Folkers, K., *J. Am. Chem. Soc.*, **77**, 251 (1955).
(42) Minot, G. R., and Murphy, W. P., *J. Am. Med. Assoc.*, **87**, 470 (1926).
(43) Perlman, D., Brown, W. E., and Lee, S. B., *Ind. Eng. Chem.*, **44**, 2000 (1952).
(44) Pfeiffer, V. F., Vojnovich, C., and Heger, E. H., *Ind. Eng. Chem.*, **46**, 843 (1954).
(45) Pierce, J. V., Page, A. C., Stokstad, E. L. R., and Jukes, T. H., *J. Am. Chem. Soc.*, **71**, 2952 (1949).
(46) Register, U. D., Rueganna, W. R., and Elvehjem, C. A., *J. Biol. Chem.*, **177**, 129 (1949).
(47) Rickes, E. L., Brink, N. G., Koniuszy, F. R., Wood, T. R., and Folkers, K., *Science*, **107**, 396 (1948).
(48) Rickes, E. L., Brink, N. G., Koniuszy, F. R., Wood, T. R., and Folkers, K., *Science*, **108**, 634 (1948).
(49) Rosenblum, C., and Woodbury, D. T., *Science*, **113**, 215 (1951).

(50) Rubin, M., and Bird, H. R., *J. Nutrition*, **34**, 233 (1947).
(51) Schmid, H., Ebnöther, A., and Karrer, P., *Helv. Chim. Acta*, **36**, 65 (1953).
(52) Sebrell, W. H., Jr., and Harris, R. S., *The Vitamins*, Academic Press, N.Y., 1954, pp. 396–523.
(53) Shorb, M. S., *J. Biol. Chem.*, **169**, 455 (1947).
(54) Smith, E. L., *Biochem. J.*, **50**, xxxvi (1951).
(55) Smith, E. L., and Parker, L. F. J., *Biochem. J.*, **43**, viii (1948).
(56) Subba-Row, Y., Hastings, A. B., and Elkin, M., *Vitamins and Hormones*, **3**, 237 (1948).
(57) Tamm, I., *Science*, **120**, 847 (1954).
(58) U.S.P. XIV, 3rd Supplement, 1951, p. 15.
(59) Veer, W. L. C., Edehausen, J. H., Wijmenga, H. G., and Lens, J., *Biochim. et Biophys. Acta*, **6**, 225 (1950).
(60) Wijmenga, H. G., Thompson, K. W., Stern, K. G., and O'Connell, D. J., *Biochim. et Biophys. Acta*, **13**, 144 (1954).
(61) Wolf, D. E., Jones, W. H., Valiant, J., and Folkers, K., *J. Am. Chem. Soc.*, **72**, 2820 (1950).
(62) Zucker, T. F., and Zucker, L. M., *Vitamins and Hormones*, **8**, 2 (1950).
(63) U.S. Pat. 2,505,053 (April 25, 1950), F. A. Kuehl and L. Chaiet (to Merck & Co.).
(64) U.S. Pat. 2,530,416 (Nov. 21, 1950), F. J. Wolf (to Merck & Co.).
(65) U.S. Pat. 2,563,794 (Aug. 7, 1951), E. L. Rickes and T. R. Wood (to Merck & Co.).
(66) U.S. Pat. 2,582,589 (Jan. 15, 1952), Fricke, H. H. (to Abbott Laboratories).
(67) U.S. Pat. 2,594,314 (April 29, 1952), F. R. Koniuszy, N. G. Brink, and K. Folkers (to Merck & Co.).
(68) U.S. Pat. 2,595,499 (May 6, 1952), T. R. Wood and D. Hendlin (to Merck & Co.).
(69) U.S. Pat. 2,607,717 (Aug. 19, 1952), N. G. Brink and F. J. Wolf (to Merck & Co.).
(70) U.S. Pat. 2,609,325 (Sept. 2, 1952), N. G. Brink and T. R. Wood (to Merck & Co.).
(71) U.S. Pat. 2,619,420 (Nov. 25, 1952), T. H. Jukes (to Am. Cyanamid Co.).
(72) U.S. Pat. 2,621,144 (Dec. 9, 1952), A. J. Holland (to Merck & Co.).
(73) U.S. Pat. 2,626,888 (Jan. 27, 1953), S. Kutosh, G. B. Hughey, and R. Malcolmson (to Merck & Co.).
(74) U.S. Pat. 2,628,186 (Feb. 10, 1953), W. Shive (to Research Corp.).
(75) U.S. Pat. 2,646,386 (July 21, 1953), C. S. Miner and B. Wolnak (to Sewerage Commission of Milwaukee).
(76) U.S. Pat. 2,653,000 (Sept. 29, 1953), A. J. Holland (to Merck & Co.).
(77) U.S. Pat. 2,650,896 (Sept. 1, 1953), L. E. McDaniel and H. B. Woodruff (to Merck & Co.).
(78) U.S. Pat. 2,678,000 (May 18, 1954), R. G. Denkewalter (to Merck & Co.).
(79) U.S. Pat. 2,703,302 (March 1, 1955), E. L. Rickes and T. R. Wood (to Merck & Co.).

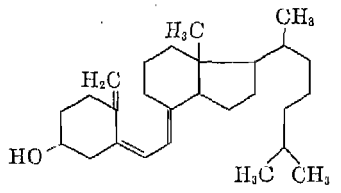
F. M. ROBINSON

VITAMIN D

"Vitamin D" is the term used to embrace all antirachitic vitamins. Since there are a number of antirachitically active compounds, it is more appropriate to speak of the *group of vitamins D* (66). At least two of this group occur naturally and are called vitamin D_2 (D-activated plant sterol, activated ergosterol) (I) and vitamin D_3 (D-activated animal sterol, activated 7-dehydrocholestrol) (II). (Formulas (I) and (II) are shown with the "point-down" orientation of the five-membered ring, and with the CH_3 and CH_2 groups written out, whereas the other formulas in this article are oriented like those under *Sterols*, with only bonds representing CH_3 and CH_2 groups.) The terms *ergocalciferol* (previously calciferol) for vitamin D_2 and *cholecalciferol* for vitamin D_3 have been adopted (1). These are also the two compounds that are manufactured on a technical scale by ultraviolet irradiation of the corresponding provitamins, *ergosterol* and *7-dehydrocholesterol*. Ergosterol is produced from yeast or molds while 7-dehydrocholesterol is synthesized from cholesterol. The various vitamins D differ from each other by slight modifications in the structure of the molecule and by some very important differences in their antirachitic effectiveness in



(I) Vitamin D_2



(II) Vitamin D_3

various animals. While vitamin D_3 can be utilized by man and by all animal species, vitamin D_2 has no usefulness in the nutrition of poultry but can be used for man and four-footed animals.

History. Deficiencies of vitamin D apparently have occurred as long ago as men existed. Some of the skeletons of prehistoric men show definite bone deformations, typical of rickets, the vitamin D deficiency disease. The cause of rickets, however, was not established until this century when it was ascertained that this disease may be cured or prevented by administration of vitamin D or by ultraviolet irradiation which produces vitamin D in the body.

Among the early writers, Palm (1890) associated through geographical studies the incidence of rickets with a deficiency of sunlight. During the period when the vitamin concept was in its formative stages, Hopkins suggested (1906) that rickets may be caused by a "dietetic factor," "well nigh as essential as are the basal constituents of diet," and Funk (1914) in his famous book "Die Vitamine" wrote: "It is very probable that rickets occurs only when certain substances in the diet essential for normal metabolism are lacking, or are supplied in insufficient amount." Experimental evidence to support this view was not known until 1919–1920, when Mellanby was able to produce rickets in puppies and to cure the disease with a "factor" contained in cod-liver oil. The importance of sunlight became appreciated at about the same time through the work of Huldschinsky, followed by that of Hess and Unger, with rachitic children. Hess and Gutman (1922) arrived at the conclusion that the curative effect of cod-liver oil and of light was fundamentally the same. Steenbock and independently Hess discovered in 1924 that antirachitic potency could be induced in foods by ultraviolet irradiation. Soon it was found that it was the sterol fraction in foods that gave rise to the antirachitic factor. By 1927 Pohl, Windaus, and Hess, and Rosenheim and Webster recognized that the known sterol ergosterol was the "provitamin D." A few years later pure "vitamin D_2" was available.

Vitamin D_2, however, was found to be of little value for chicks, while cod-liver oil was highly active. Windaus and his associates in 1935 synthesized 7-dehydrocholesterol from cholesterol and showed that this provitamin D upon ultraviolet irradiation gave rise to vitamin D_3, which was found to be identical with the vitamin D present in fish-liver oils.

Provitamins D

The provitamins D are compounds that can be activated to vitamins D. Chemically they belong to the class of sterols (see Vol. **12**, p. 917). The provitamins D are not known to have any physiological function of their own. They can, however, be synthesized by the animal organism as well as by plants. They can apparently be transported within the animal body and a certain amount is deposited in the skin where sunlight can reach the provitamin and convert it into vitamin D. Certain foods and

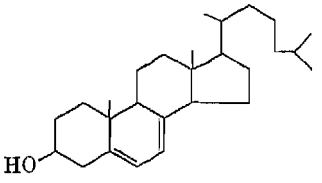
feeds contain small amounts of provitamins D and it is assumed that the provitamins are absorbed from the intestinal tract. There are a considerable number of naturally occurring provitamins D, but the exact number and the constitution of several of those that have been isolated is unknown. In addition, several provitamins D have been synthesized from various sterol compounds. Those that have been sufficiently identified, either chemically or biologically after transformation to the corresponding vitamins D, are listed below (see also Vol. **12,** pp. 922–24).

7-Dehydrocholesterol (III), $C_{27}H_{44}O$, m.p. 150–51°C., $[\alpha]_D^{20}$ −113.6° ($CHCl_3$) (8).

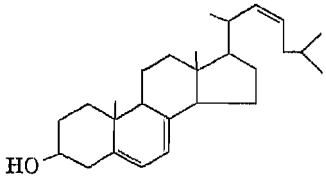
5,7,22-Cholestatrien-3β-ol (IV), $C_{27}H_{42}O$, has not as yet been isolated or synthesized.

22,23-Dihydroergosterol (V), $C_{28}H_{46}O$, m.p. 152–53°C., $[\alpha]_D^{20}$ −109° ($CHCl_3$) (39).

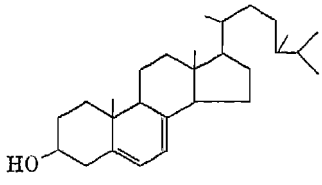
7-Dehydrocampesterol (VI), $C_{28}H_{46}O$, m.p. 165°C., $[\alpha]_D$ −109° is the 24α-epimer of 22,23-dihydroergosterol. So far this provitamin D has not been found in nature, but has been synthesized from campesterol (29).



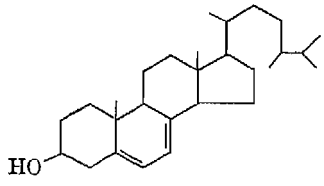
(III) 7-Dehydrocholesterol



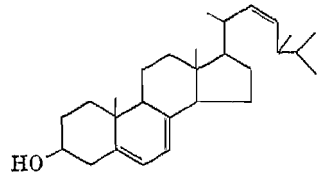
(IV) 5,7,22-Cholestatrien-3β-ol



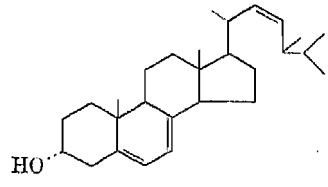
(V) 22,23-Dihydroergosterol



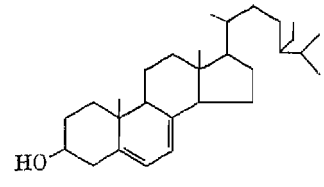
(VI) 7-Dehydrocampesterol



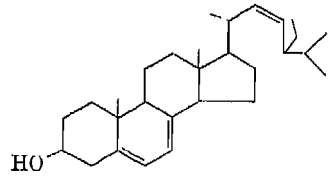
(VII) Ergosterol



(VIII) Epiergosterol



(IX) 7-Dehydro-β-sitosterol



(X) 7-Dehydrostigmasterol

Ergosterol (VII), $C_{28}H_{44}O$, m.p. 165°C., $[\alpha]_D^{20}$ −130° ($CHCl_3$), crystallizes from alcohols and acetone in small colorless plates with water of crystallization. From anhydrous solvents, for example from ethyl acetate or ether, ergosterol crystallizes in

the form of fine needles. The melting point varies according to the degree of hydration. The best crystallized preparation contains $1\frac{1}{2}$ moles of water and melts at 168°C. (5). Complete dehydration is very difficult to achieve and results in a product with a melting range of 166–183°C. Ergosterol distills in high vacuum at 250°C. without decomposition.

Epiergosterol (VIII), $C_{28}H_{44}O$, physical constants unknown, is a synthetic product (38).

Corbisterol, $C_{28}H_{44}O$ (?), is of unknown constitution, perhaps the 24-epimer of ergosterol (32), m.p. 149°C., $[\alpha]_D$ −93.5°.

7-Dehydro-β-sitosterol (IX), $C_{29}H_{48}O$, m.p. 144–145°C., $[\alpha]_D^{20}$ −116° ($CHCl_3$), has not been found in natural sources but is believed to occur in plant oils (44).

7-Dehydroclionasterol, $C_{29}H_{48}O$, m.p. 138°C., $[\alpha]_D$ −98° ($CHCl_3$), is the 24-epimer of 7-dehydrositosterol (4).

7-Dehydrostigmasterol (X), $C_{29}H_{46}O$, m.p. 154°C., $[\alpha]_D$ −113° (C_6H_6), has not been isolated but is probably present in provitamin D mixtures of plant origin (16).

PROPERTIES

All provitamins D have similar solubility characteristics. They are insoluble in water, but soluble in the typical organic solvents such as ethers, hydrocarbons, and

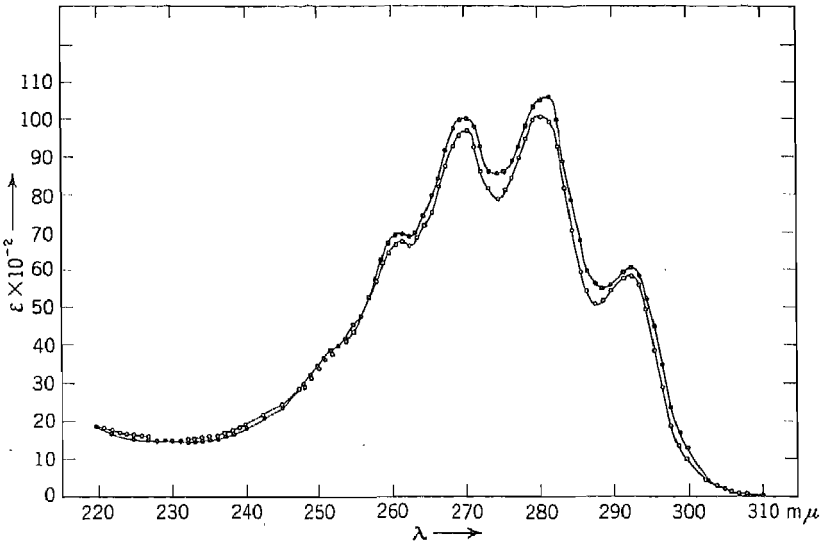


Fig. 1. Absorption spectrum of ergosterol in ethyl alcohol (black circles) and isooctane (open circles) (66).

fats. The lower alcohols are usually used for recrystallization. Ergosterol is soluble to the extent of one part in 526 parts of cold ethyl alcohol, 36 parts of boiling ethyl alcohol, 200 parts of cold acetone, 32 parts of hot acetone, 50 parts of ether at 20°C., and 28 parts of ether at the boiling point (3).

The provitamins D have a characteristic absorption spectrum in the ultraviolet with maxima at 260, 270, 281, and 293.5 mμ (Fig. 1) (14). An excellent method for the quantitative determination of provitamins D is based upon the measurement of the extinction coefficient of the four well-defined maxima of the absorption spectrum.

The molecular absorption coefficient K is about 30×10^3 for the band at 281 mμ. Table I shows the extinction coefficients of the maxima as well as of the minima for 7-dehydrocholesterol (14).

TABLE I. Absorption Characteristics of 7-Dehydrocholesterol in Ethyl Alcohol.

mμ	ε	$E^{1\%}_{1\text{ cm.}}$
Min. 230	1,500	39.1
Max. 262.5	7,400	193
Max. 271	10,400	271
Min. 276	8,830	230
Max. 281.5	10,750	280
Min. 288	5,530	144
Max. 293	6,150	160
Min. 321	36	0.9

OCCURRENCE

Provitamins D are found throughout the animal and plant kingdom (see Tables II, III, IV). While it is impossible to make definite statements as to which provitamin D occurs in a specific natural source, certain generalizations can be made. It appears that the most prevalent provitamin D in higher animals is 7-dehydrocholesterol. Available evidence indicates that 7-dehydrocholesterol or a provitamin D giving rise to a vitamin D of similar physiological activity is present in the skin of man and also of birds (27a). Plants, molds, and yeasts, on the other hand, contain predominantly ergosterol. 22,23-Dihydroergosterol has been found in ergot together with ergosterol (30). There is considerable variation and some uncertainty about the kind of provitamin D in lower animals. Thus, ergosterol has been found in the snail *Arion empiriocorium* and in the earthworm, and 7-dehydrocholesterol in the snail *Buccinum undatum* (7). A mixture of several provitamins D seems to occur in several mollusks. In the European edible mussel, *Mytilus edulis*, for example, ergosterol and 7-dehydrocholesterol and 5,7,22-cholestatrien-3β-ol have been found (34). The provitamin D occurring in the American mussel *Modiolus demissus* appears to be different from the identified provitamins (28) and may also be a mixture. Corbisterol has been discovered in the bivalve *Corbicula leana* (17), and 7-dehydroclionasterol is believed to occur in the periwinkle (15).

The amount of provitamin D in the various natural sources varies considerably. Thus, in higher animals, the provitamin D content is the greatest in the skin, where it may reach up to 4% of the total sterol content. The inner organs usually contain appreciably smaller amounts, ranging from less than 0.1 to 0.5%. Invertebrata as a rule contain higher amounts of provitamin D than vertebrata. The highest concentration of 7-dehydrocholesterol, 27% of the total sterols, has been found in a species of snails, *Buccinum undatum*. The sterols isolated from the mussel *Modiolus demissus* contain 40–50% of provitamin D, which made this species an attractive source of provitamin D for commercial production (57).

The best sources of **ergosterol** are yeasts and molds. Its occurrence in ergot is historically important, but the amount obtainable from this source is not sufficient for commercial manufacture. On the other hand, ergosterol occurs in relatively large amounts in yeasts (*q.v.*), and extensive studies have shown that the yield can be influenced to an appreciable extent by the conditions under which the yeast is grown.

The strain of yeast is also of some importance. Other commercially used natural sources of ergosterol are the mycelia of certain molds, especially of *Aspergilli* and *Penicillia*. As a by-product of citric acid fermentation (see Vol. **6,** 365), *Aspergillus niger*

TABLE II. Ergosterol Contents of Various Materials.

Source	Provitamin D in sterols, %
Dried yeast	90–100
Snail (*Arion empiricorium*)	19–25
Earthworm	22
Cottonseed oil	5
Scopolia root	1.4

TABLE III. 7-Dehydrocholesterol Contents of Various Materials.

Source	Provitamin D in sterols, %
Pigskin	3–6
Snail (*Buccinum undatum*)	17–27

TABLE IV. Provitamin D Contents of Various Materials.

Source	Provitamin D in sterols, %
Vertebrata	
Skin from man	0.15–0.43
cattle	0.18
calf	0.68
mice	0.87
chicken feet	1.0–4.0
chicken trunk	0.001–0.01
Blood serum (cow)	0.15
Brain (cow)	0.01
Lung (calf)	0.025
Heart (calf)	0.032
Spleen (cow)	0.045
Placenta (cow)	0.18
Pancreas (cattle)	0.18
Invertebrata	
Ribbed mussel (*Modiolus demissus*)	40–50
Lugworm (*Arenicola marina*)	4–12
Mussels (*Mytilus edulis*)	9–10
Oysters	5–6
Leech	4
Crabs (*Cancer pagurus*)	0.32
Sea anemones	2–10
Plants	
Cocksfoot grass	0.80
Rye grass	1.5
Wheat germ oil	0.8
Seaweed	0.008
Cabbage	0.05
Spinach	1.0
String beans	0.1

is an attractive source material (45). The commercial production of penicillin (*q.v.*) provides a readily available source of *Penicillium mycelium*.

ISOLATION

Isolation procedures are commercially important since ergosterol is manufactured only by this method. The end product in this case is about 90–100% pure. The yield in a commercial operation has been described as 2.5–3% of the yeast used as the starting material. Commercial ergosterol often contains up to 5% of 5,6-dihydroergosterol. In the commercial production of mussel provitamin D as practiced in Europe, using *Mytulis edulis* (50), or as practiced in the U.S., using *Modiolus demissus* (57), the total sterols, containing the provitamin, are isolated, but the pure provitamin D is not separated.

In general, however, the isolation of provitamins D from natural sources involves two different steps: the isolation of the total sterols and the separation of the provitamins from other sterols. The isolation of the total sterols is usually a relatively simple process and consists in either first extracting the total fat, followed by alkaline saponification of the fatty material and isolation of the unsaponifiable fraction by extraction with ether or di-*n*-butyl ether, or in saponifying directly the total material followed by isolation of the nonsaponifiable fraction. The isolation of the sterols from the unsaponifiable fraction is carried out by crystallization from a suitable solvent, such as acetone and alcohol. Ethylene dichloride (20 parts) or a mixture of this with methanol has been used commercially for recrystallization. Special isolation procedures have been developed for special cases. For example, after saponification, the fatty acids may be precipitated as calcium salts which adsorb the sterols. These are then recovered by solvent extraction from the filtered and dried precipitate.

The separation of the provitamins from other sterols is usually a difficult problem and success depends largely upon the type and amount of provitamin D present. Of commercial importance is the purification of ergosterol, which is usually achieved by recrystallization from benzene-alcohol. This is not too difficult since the crude sterols contain around 90% of the provitamins. On the other hand, when very little provitamin D is present, isolation is often difficult or impossible. Thus no method is known by which the provitamin D in the spinal cord of cattle can be isolated. In this case the sterols consist essentially of cholesterol and contain provitamin D only to the extent of about 0.1%. Better chances for a successful isolation exist when the provitamin D is present in a concentration of at least 4–5%. The usual method is fractional adsorption of the sterols or of their esters, for example on alumina, which sometimes permits an almost quantitative separation (54). Separation of the provitamins D from the sterols of the ribbed mussel has been achieved by fractional crystallization from isopropyl alcohol (26). Of scientific interest is also the method of forming a difficultly soluble condensation product of the provitamin D with maleic or citraconic anhydride, which after separation from the much more soluble sterols is split by thermal decomposition into the provitamin D and the acid anhydride.

SYNTHESIS

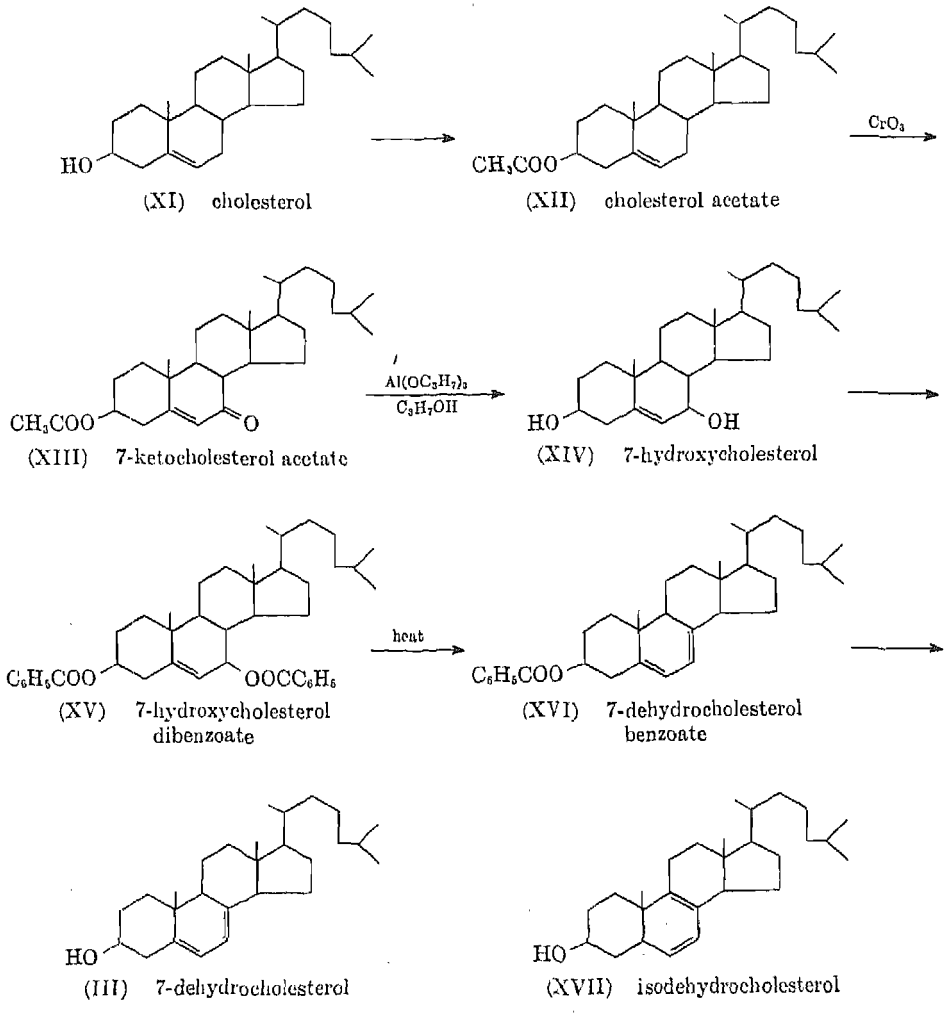
Procedures for the synthesis of provitamins D are of considerable technical importance. Of the two types of vitamin D manufactured commercially, only one provides a source of antirachitic activity for all animal species, including chickens and turkeys. This type is produced by D-activation of animal sterols. The prototype of

this class is vitamin D_3, which is manufactured from 7-dehydrocholesterol. Although there are good natural sources of animal provitamins D available for commercial production, the synthetic route is usually preferable because of easier control of process and product.

7-Dehydrocholesterol can be manufactured by a variety of procedures. All such methods use cholesterol (see Vol. **12,** pp. 921, 945) as the starting material. There is no total synthesis of 7-dehydrocholesterol or of any other provitamin D.

The conversion of cholesterol to 7-dehydrocholesterol, in its simplest aspect, involves the removal of two hydrogen atoms from the cholesterol molecule. This can be accomplished by a one-step oxidation or dehydrogenation step (47). Historically, this was the first synthesis of a provitamin D, but this process was soon supplanted by what has become known as the classical synthesis of 7-dehydrocholesterol by Windaus. The original Windaus synthesis gave a yield of about 4% of 7-dehydrocholesterol (48). Following the principle of this process many modifications were introduced that re-

SCHEME 1



(XI) cholesterol

(XII) cholesterol acetate

(XIII) 7-ketocholesterol acetate

(XIV) 7-hydroxycholesterol

(XV) 7-hydroxycholesterol dibenzoate

(XVI) 7-dehydrocholesterol benzoate

(III) 7-dehydrocholesterol

(XVII) isodehydrocholesterol

sulted in a commercial process for 7-dehydrocholesterol with a yield of many times that of the original procedure.

The *Windaus process* is as follows (see Scheme 1): Cholesterol (XI) is converted into cholesterol acetate (XII) which is oxidized with chromic acid to 7-ketocholesterol acetate (3β-hydroxy-5-cholesten-7-one acetate) (XIII). The latter upon reduction with aluminum isopropoxide yields 7-hydroxycholesterol (5-cholestene-3β,7-diol) (XIV), the acetyl group undergoing an ester interchange with the isopropyl alcohol used as the solvent. The 7-hydroxy compound is benzoylated and the dibenzoate (XV) is thermally decomposed into 7-dehydrocholesterol benzoate (XVI) and benzoic acid. The former upon saponification yields 7-dehydrocholesterol (III).

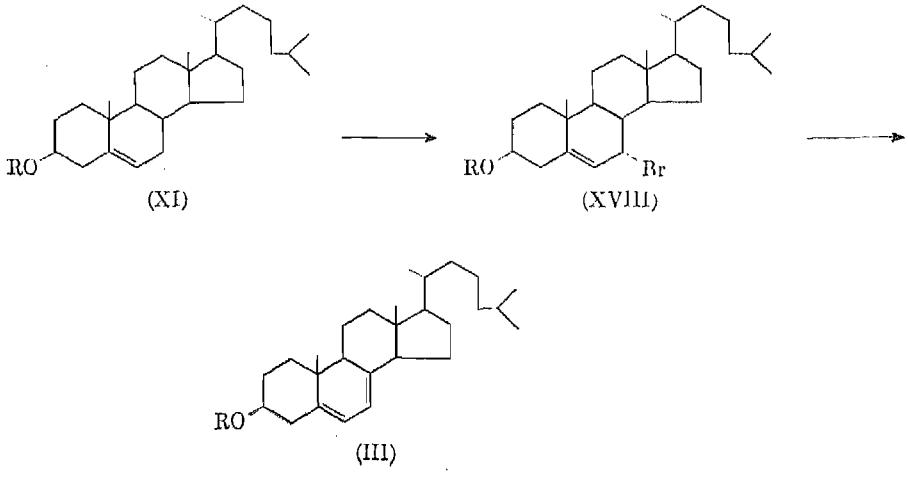
This series of reactions takes a different course when the benzoate, instead of the acetate, of cholesterol is used. Upon reduction of 7-ketocholesterol benzoate, obtained by chromic acid oxidation of cholesterol benzoate, the 3-monobenzoate of 7-hydroxycholesterol is formed (52).

Other important modifications comprise oxidation of the cholesterol ester to the 7-keto compound in a buffered system (61); reduction of the keto to the hydroxy derivatives with aluminum isopropoxide under carefully controlled conditions in the presence of an amine (56), or with aluminum lithium hydride; and splitting of benzoic acid from the 7-hydroxy dibenzoate in the presence of a solvent and an acid acceptor (51,53,55).

The 7-hydroxycholesterol obtained by reduction of the 7-keto derivatives is a mixture of the two possible geometric isomers. The 7α-form makes up about 80–90% of the mixture. The 7β-form has also been obtained by direct oxidation of the monocholesterol ester of phthalic acid by permanganate oxidation. 7-Hydroxycholesterol can be prepared in relatively low yields by oxidation of cholesterol with such oxidizing agents as lead tetraacetate, peroxybenzoic acid, and molecular oxygen (58).

Either of the two isomers of 7-hydroxycholesterol can be converted into 7-dehydrocholesterol. As a by-product of this reaction, isodehydrocholesterol is obtained, differing from 7-dehydrocholesterol only in the position of the conjugated double bonds. (Formula XVII shows the double bonds in the 6,7- and 8,9-positions.)

SCHEME 2



(XI) (XVIII) (III)

Isodehydrocholesterol can be partially converted into 7-dehydrocholesterol by heat treatment (59).

A somewhat different process known as the *Ziegler process* is also used commercially. This is based on Ziegler's method for the introduction of a double bond adjacent to an existing one by introducing a bromine through reaction with *N*-bromosuccinimide. This is followed by dehydrobromination. The application of this procedure to cholesterol (60) has been developed both in the U.S. and abroad simultaneously. (See Scheme 2; see also Vol. **12,** pp. 928–30.)

ASSAY

There are a number of **chemical methods** that may be used for the qualitative or semiquantitative determination of provitamins D. All these methods are based on chemical reactions given by sterols with conjugated double bonds in or about the positions of the double bonds in the provitamin D molecule. This means that none of these methods is absolutely specific for the provitamins and that there is no method that can be used to differentiate between individual provitamins.

(*1*) *The Reversed Salkowski Reaction.* The provitamin D is dissolved in chloroform and concentrated sulfuric acid is added. The acid becomes deep red while the chloroform layer remains colorless. Sterols, such as cholesterol and sitosterol, give the opposite color reactions: the chloroform becomes red, while the acid exhibits a green fluorescence.

(*2*) *The Liebermann-Burchard Reaction.* The provitamin D is dissolved in chloroform, and acetic anhydride and concentrated sulfuric acid are added dropwise. A red color develops which progressively changes from blue-violet to green. Cholesterol gives a similar change of color but the initial red color remains unchanged for a longer period of time.

(*3*) *The Tortelli-Jaffé Reaction.* A solution of provitamin D in acetic acid is mixed with a 2% solution of bromine in chloroform. A green color develops. This reaction is given by steroids with a di-tertiary ethenoid linkage and by vitamins D.

(*4*) *The Rosenheim Reaction.* To a solution of provitamin D in chloroform a solution of trichloroacetic acid in water is added. A red color develops which changes slowly into a light blue. This color reaction becomes considerably more sensitive when, before the addition of the trichloroacetic acid, lead tetraacetate in glacial acetic acid is added to the chloroform solution of the provitamin. An intense green fluorescence occurs which is, however, not given by provitamin D esters. Thus, provitamins D can be differentiated from their esters by this method. This modified color reaction can be employed for the detection of provitamins D in an amount of the order of 0.1 γ.

(*5*) *Chloral Hydrate Reaction.* Crystals of provitamin D, when heated slowly with crystals of chloral hydrate, melt about 50°C., and the mixture becomes first red, then green, and finally deep blue. Sterols, such as cholesterol, do not give any color reaction with chloral hydrate.

(*6*) *The Antimony Trichloride Reaction.* Provitamin D dissolved in chloroform and mixed with a solution of antimony trichloride in chloroform yields a red color.

(*7*) *The Chugaev Reaction.* A solution of provitamin D in glacial acetic acid with an excess of acetyl chloride and zinc chloride yields upon heating to the boiling point an eosin-red color with a greenish yellow fluorescence. The sensitivity is reported to be 1:80,000.

While none of these reactions is absolutely quantitative, the Liebermann-Burchard reaction and the Rosenheim reaction have been recommended and developed for quantitative assays.

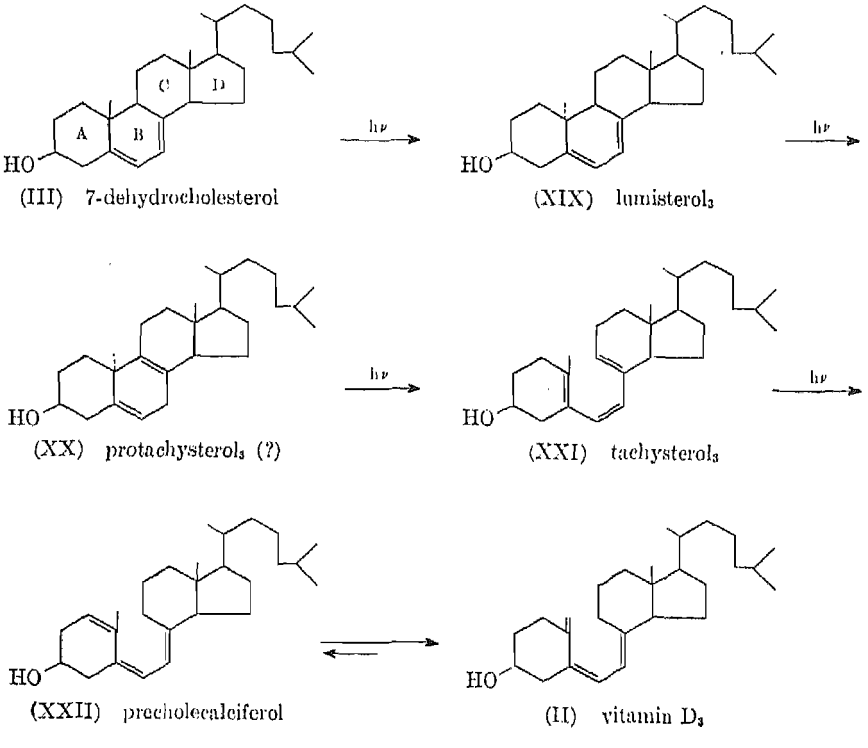
The most accurate method for the determination of provitamins D is the **spectroscopic analysis.** The characteristic absorption spectrum of the provitamins in the ultraviolet region is the same for all provitamins on a molecular basis (see p. 831). This method, while quite accurate for the determination of provitamins D in sterol mixtures isolated from natural sources, cannot distinguish between the individual provitamins D. This method can also be used for the determination of provitamins D in preparations obtained by chemical synthesis with the restriction that the actual absorption maxima must be determined as such and in relation to each other and that general absorption must be observed and properly considered.

Conversion of Provitamins D to Vitamins D

Provitamins D can be activated to vitamins D by a number of different processes. They all involve in principle the input of energy into the provitamin D molecule. Thus, ultraviolet light, cathode rays, radium emanation, etc., effect activation.

Mechanism and Chemistry of Activation. The conversion of provitamins D to vitamins D is not a simple process but a complex sequence of rearrangements without parallel in photochemistry. During the course of this reaction several substances are formed before vitamin D is obtained, and the latter is not stable to the activating energy but is transformed into other compounds.

SCHEME 3



(III) 7-dehydrocholesterol (XIX) lumisterol$_3$

(XX) protachysterol$_3$ (?) (XXI) tachysterol$_3$

(XXII) precholecalciferol (II) vitamin D$_3$

Extensive studies indicate that the conversion is identical for all provitamins. The sequence of reactions that occurs when 7-dehydrocholesterol is irradiated with ultraviolet light will be discussed as typical. When other processes of activation are used, the same vitamin D is obtained and presumably also the same intermediates, but this is not known.

In the process of activation of 7-dehydrocholesterol (III, Scheme 3) (42), the first photochemical reaction constitutes an inversion of the C(10)-methyl group from the β- to the α-position, yielding *lumisterol*$_3$ (XIX). Irradiation of lumisterol causes the opening of ring B of the sterol molecule between carbon atoms 9 and 10, with simultaneous formation of a double bond. The first product is believed to be a compound called *protachysterol*$_3$ (tentative formula (XX)), which rearranges to *tachysterol*$_3$ (XXI). The double bonds of the latter rearrange under the influence of irradiation to give *precholecalciferol* (XXII), which in turn rearranges to vitamin D$_3$ (II) (35). This

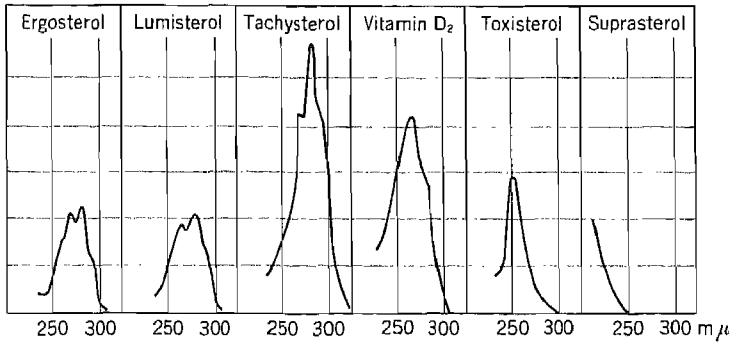


Fig. 2. Absorption spectra of ergosterol and its irradiation products in 0.2% ether solution (66).

last reaction apparently does not require ultraviolet but occurs spontaneously. It is a slow reaction which is greatly accelerated by the heat usually applied in concentrating and isolating the vitamin. This reaction has been described as reversible; at the point of equilibrium the vitamin predominates over its isomer.

The vitamins D, upon further irradiation, are converted into compounds that are devoid of antirachitic activity just as all the transformation products of the provitamins D with the exception of vitamin D itself have no vitamin activity. The products of the irradiation of vitamin D are called *suprasterol I and II*, but their chemical constitution is unknown.

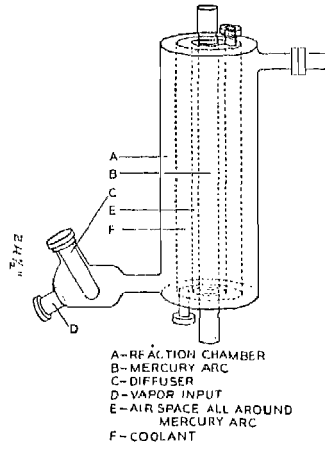
All the irradiation products from the provitamins to the suprasterols are isomers. The changes that occur within the molecule can be followed spectroscopically (see Fig. 2) (41).

Biological Significance. Although provitamins D occur and are synthesized in the animal organism, the conversion of the provitamin D to vitamin D can only be accomplished by the ultraviolet radiation of the sun or some artificial source. In order to derive the needed vitamin in adequate amounts, the provitamin is usually found in relatively high concentration in the skin. Feather- and fur-bearing animals carry the provitamin D in the skin of the uncovered part of the body. For example, chickens have a very high concentration of provitamin D in their feet (27a).

PROCESS OF ACTIVATION

Ultraviolet Light Activation. Provitamins D are activated to vitamins D by ultraviolet light of the same wave lengths as the rays absorbed by the provitamins as evident from the absorption spectrum. The energy required to produce one U.S.P. unit of vitamin D from ergosterol has been repeatedly investigated. The data obtained under the most careful conditions indicate that 7.5×10^{13} quanta will produce one U.S.P. unit of vitamin D. In the active region, the energy necessary depends upon the wave length. The most effective activation of ergosterol is obtained from light of wave length 281 mμ, which is the line that shows maximum absorption of ergosterol.

Different sources of ultraviolet light used for the activation of provitamins D are the magnesium arc, the carbon arc, and the mercury-vapor lamp. The light emitted by a bismuth-vapor lamp has also been recommended. Cored carbon electrodes impregnated with various metals are also used.



Courtesy Hanovia Chemical & Manufacturing Co.

Fig. 3. Quartz irradiation vessel for the conversion of provitamin D to vitamin D.

Provitamins D can be activated in the dry state, in vapor form, and in solutions. Irradiation of provitamin D in the dry state gives poor yields because the vitamin D is produced only on the surfaces of the crystals and further irradiation destroys the vitamin D formed before the provitamin D inside the crystals has been affected. Irradiation in the vapor phase has not been investigated thoroughly. The best method of irradiation is to expose solutions of provitamins D to the action of the ultraviolet light. Agitation of the solution was found to increase the vitamin D yield. The best technical method known today involves the utilization of a special quartz irradiation chamber which is built concentrically around the mercury-vapor lamp and through which the provitamin D solution passes continuously in turbulent flow (see Fig. 3).

It is well established that light of wave length between 275 and 300 mμ produces the best yields of vitamin D with the smallest amount of by-products. The desired light is obtained by special light filters. Light below 275 mμ is filtered out by aromatic compounds such as benzene or xylene or by compounds such as biphenyl in benzene solution, or by a 5% lead acetate solution. Carbon tetrachloride is used to filter out light of the wave lengths 312 and 313 mμ. Special types of glass that selectively allow light of 270–300 mμ to pentrate can also be made.

The presence of oxygen during the irradiation should be carefully avoided. The intermediates and by-products formed during the irradiation are much more susceptible to oxidation by molecular oxygen than either the provitamins or the vitamins D. The presence of oxygenated materials makes it difficult to isolate crystalline vitamin D, but the actual yield is not greatly affected.

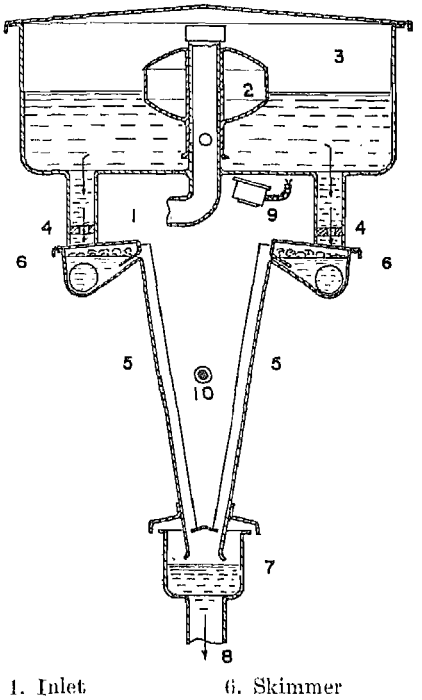
There is apparently also a specific solvent effect involved in the irradiation procedure. The activation takes place more rapidly in ether than in alcohol. Other solvents such as cyclohexane and the cyclic diether dioxane have also been recommended, either alone or in mixture with ethyl acetate, benzene, or triethanolamine. Provitamins D can also be irradiated in oil solution.

Of further interest are some special methods of irradiation. Thus, it is claimed that increased yields of vitamin D are obtained when compounds are added that protect the vitamin D after its formation. Ethylene or alkalies have been used in this manner. The irradiation can also be carried out in the presence of photosensitizers, for example, eosin, erythrosin, or dibromodinitrofluorescein.

The temperature coefficient of activation, if any, is very small. The greater effect observed on irradiation at the boiling point of the solvent is probably due to more uniform activation of all molecules present.

The best yields are obtained when only 40–60% of the total provitamin D is converted. In such cases, the yields are between 30% and 60% of theory. This calculation includes the recovery of unchanged provitamin D.

Besides the irradiation of solutions of provitamins D, the irradiation of foods and feed is of technical importance. Thus, cereals and flour have been commercially irradiated. Of considerable importance for human consumption is the irradiation of milk (see also *Dairy products (milk)*, Vol. 4, p. 789). Special equipment has been designed to obtain optimum yield by irradiation of the milk flowing in a thin layer (see Fig. 4). Ultraviolet light penetrates milk only very slightly and the odor of milk is very easily affected adversely by exposure to the light. Also technically important is the irradiation of yeast, which is carried out in equipment similar to that for milk irradiation. A slurry of yeast in water is circulated through the equipment a number of times until the required degree of D-activation occurs. The irradiated material is spray-dried.



1. Inlet
2. Float
3. Tank
4. Fixed Gate
5. Flow Board
6. Skimmer
7. Collecting Tank
8. Outlet
9. Photocell
10. U.V. Burner

Courtesy Hanovia Chemical & Manufacturing Co.

Fig. 4. Diagram of commercial milk irradiation equipment.

Activation by Other Means. Although activation by ultraviolet light is the best-known procedure, other methods have been investigated for the conversion of provitamins D to vitamins D. Activation of ergosterol vapors by high-frequency electrons was used commercially for a short time.

Cathode rays as such or in the presence of catalysts such as iron uranium salts; canal rays; α-, β-, and γ-rays of radioactive elements; radium emanation; x-rays, corpuscular rays; high-frequency electrons; and finally alternating current of high frequency have been claimed to effect activation of provitamins D.

Vitamins D

Of the considerable number of different vitamins D, exactly how many occur in nature is not known. By molecular distillation of cod-liver oil evidence for the

existence of six different vitamins D has been obtained (13). Two of these, vitamins D_2 and D_3, constitute the major amount of the antirachitic activity. Two other compounds were found to be present in smaller amounts, and another two appeared to be present only in traces. On the basis of the findings from molecular distillation of different fish oils it was concluded that the vitamin D composition of such oils is not uniform and that there may be vitamins D not encountered in the cod-liver oil originally investigated.

Prior to the isolation of any antirachitic substance from natural material, several forms of vitamin D were obtained by activation of different provitamins D. Numbers were assigned to these vitamins D in order to simplify the nomenclature. There is, however, no vitamin D_1 because the compound to which this term was originally assigned was later shown to be a molecular addition product of vitamin D_2 with lumisterol. The relation of the other vitamins D to their provitamins is shown in Table V.

TABLE V. Relation of Vitamin D to Provitamin D.

Vitamin D	Provitamin D	Remarks
Vitamin D_2	Ergosterol	
Vitamin D_3	7-Dehydrocholesterol	
Vitamin D_4	22,23-Dihydroergosterol	
Vitamin D_5	7-Dehydro-β-sitosterol	
Vitamin D_6	?	Found in cod-liver oil (66,27)
Vitamin D_7	?	

From a practical point of view, the vitamins D are differentiated according to the general source of the provitamin from which they can be obtained, namely, animal-type and plant-type vitamin D. Vitamin D_3 is the representative of the animal-type vitamin D, while vitamin D_2 represents the plant-type. Feed manufacturers often use the terms "D-activated animal sterols" and "D-activated plant sterols." This differentiation by origin is necessary since in the nutrition of poultry only the animal-type vitamin D is of practical value.

PROPERTIES

All the known vitamins D, in the pure state, are white, odorless crystals. They are very soluble in fats and in the usual organic solvents such as ether, chloroform, and benzene, somewhat less so in acetone and ethyl alcohol, and slightly soluble in methanol. They are insoluble in water. They exhibit a characteristic absorption spectrum in the ultraviolet region with one maximum at 265 mμ, ϵ = 19,200 (for vitamin D_3). (Extinction coefficient 470–500.)

Vitamin D_2: m.p. 115–117°C., $[\alpha]_D^{20}$ + 105° (96% alcohol) (33).

Vitamin D_3: m.p. 82–86°C. (range), $[\alpha]_D^{20}$ + 111.2° (96% alcohol) (33).

Vitamin D_4: m.p. 107–108°C., $[\alpha]_D^{20}$ + 89.3° (acetone) (40).

The melting points of the vitamins D are relatively difficult to determine accurately. Depending upon the method used, considerably different results may be obtained. Reproducible data may be obtained by using whole, dry crystals (not pulverized), by avoiding exposure to air, sealing the capillary melting point tube, inserting the tube in the melting point apparatus at a temperature about 10° below the melting point, and permitting a rise of temperature of 5°C. per minute.

The vitamins D are relatively stable against oxidation when pure, but oxidize

easily in the presence of the other irradiation products of the provitamins D. They are stabilized, however, in oil solution. They are destroyed by light and by excessive heat although they are comparatively stable to heat treatment, especially in neutral or alkaline solution. Acidity slowly destroys these vitamins. The vitamins D can be sublimed in high vacuum, although partial decomposition may occur. Two thermal conversion products, *pyrocalciferol* and *isopyrocalciferol* (having the same empirical formulas as the vitamins D), are obtained by heating to 160–190°C.

OCCURRENCE

Vitamin D occurs in small amounts in most animals. Significant amounts, however, are found only in the liver and the viscera. Milk and eggs are natural carriers of vitamin D.

Abundant and technically important amounts of vitamin D are found only in fish livers and viscera. The concentration of this vitamin in liver oil varies considerably with the species, the season, and a number of other biological factors such as age, climate, and food supply. Halibut livers, for example, in the summer months give a high yield in oil of low potency, and in the winter months they give less oil with more vitamin D. Fish with much body oil are the richest natural source of vitamin D. The distribution of vitamin D in various fish oils is illustrated in Table VI (6). While the fat from fish contains relatively large amounts of vitamin D, the fat of other animals contains little or none. Exceptions to this general rule are the fats of animals which live upon fish, such as certain birds.

Vitamin D does not occur in plant tissues. No detectable amount has ever been found in fresh vegetables. Certain plant materials contain significant amounts of provitamin D and it seems quite possible that some vitamin D should be formed by irradiation from the sunlight. The antirachitic properties of hay, dried alfalfa, and cacao shells are due to the growth of molds or yeasts capable of synthesizing relatively large amounts of provitamin D, which is partly converted into vitamin D during "sun curing."

TABLE VI. Distribution of Vitamin D in Various Fish Oils.

Name of fish	Scientific name	Vitamin D, I.U./g.
Frigate mackerel	*Auxis thazard*	44,000
California bluefin tuna	*Thunnus saliens*	42,000
Bonito	*Sarda lineolata*	35,000
Albacore	*Thunnus germo*	13,000
Jewfish	*Stereolepis gigas*	9,000
Swordfish	*Xiphius gladius*	7,000
Barracuda	*Sphyraena argentea*	4,700
Sardine (pilchard)	*Sardinia caerulea*	2,300
Halibut	*Hippoglossus hippoglossus*	1,200
Striped perch	*Taeniotoca lateralis*	900
Round-nose sole	*Eopsetta jordani*	520
Black cod	*Anoplopoma fimbria*	310
Pacific cod	*Gadus macrocephalus*	190
Atlantic cod	*Gadus morrhua*	100
Pacific dogfish	*Squalus suckleyi*	13
Basking shark	*Cetorhinus maximus*	6
Atlantic dogfish	*Squalus acanthias*	3

ISOLATION

Pure vitamin D is not isolated commercially from natural sources. Before the development of "D-activated animal sterols" or of vitamin D_3, concentrates of vitamin D were produced from fish livers. While this industry still constitutes an important source of vitamin A, the importance in the vitamin D field is reduced, at least in the U.S., to the preparation of a few pharmaceutical specialties such as cod-liver oil and percomorph liver oil. The technical processes used, saponification of the oils, isolation of the vitamin D-bearing unsaponifiable matter, and molecular distillation are described under *Fish-liver oils*. Procedures used for the isolation of the pure vitamin D_2 or vitamin D_3 for identification and for scientific studies may be found in technical monographs such as reference (66). In general, they consist of the methods described for the preparation of vitamin A and D concentrates from fish oils followed by procedures similar to those described below for the manufacture of crystalline vitamin D.

MANUFACTURE

The bulk of the vitamin D on the market in the U.S. is manufactured by ultraviolet irradiation of the provitamins (see p. 840). Commercially, the provitamin D is activated in ether solution in the case of animal sterols, 7-dehydrocholesterol, and ergosterol, or as a water slurry in the case of yeast. When an ether solution containing a provitamin D is irradiated, the progress of the activation can be determined by following the change in optical rotation of the mixture in solution, by crystallization of the unchanged provitamin, or by its precipitation with digitonin. While these procedures determine only the rate of conversion of provitamin D to vitamin D, they are much quicker than any biological estimation of the amount of vitamin D formed. After irradiation the solvent is removed and the unchanged provitamin is recovered by crystallization from alcohol. The isolation of the vitamin D formed is carried out in the absence of oxygen. For the manufacture of a solution of vitamin D in oil, the alcoholic vitamin D solution is added to the oil and the alcohol is removed by vacuum distillation. Corn oil is used to a great extent for animal feeding oils because of the great antioxidant power it possesses. Fish oils are also used, especially those high in vitamin A but low in vitamin D in order to increase their antirachitic activity. For pharmaceutical preparations olive oil, sesame oil, and peanut oil are also used.

For the manufacture of crystalline vitamins D, use is made of a characteristic, sparingly soluble ester such as the 3,5-dinitrobenzoate. This can be purified by fractional crystallization, and the pure vitamin D is obtained by careful saponification of the ester (46,49).

According to the U.S. Tariff Commission, the U.S. production of vitamin D_2 in 1953 was 25,824 billion U.S.P. units, and the sales totaled 23,147 billion. The corresponding figures for vitamin D_3 were 24,244 and 21,713 billion U.S.P. units. In 1955 wholesale prices for high-potency vitamin D_2 oils and vitamin D_3 oils were 2.5¢ and 3¢, respectively, per Standard Unit. Ergosterol sold for $150/kg.

STANDARDS AND ASSAY

Pure vitamin D_3 was adopted in 1949/1951 as the new International Standard (43) as well as the U.S.P. standard. By definition, one unit of vitamin D activity is represented by 0.025 γ of vitamin D_3. Therefore one gram of vitamin D_3 equals 40 million U.S.P. units. The International Chick Unit (I.C.U.) of vitamin D is also identical with the U.S.P. unit (24).

Before 1951, two different standards for vitamin D had to be recognized because of the different species activity. The I.U. and the U.S.P. unit of vitamin D was a measure only of the plant-type vitamin D, one unit being by definition 0.025 γ of vitamin D_2. The A.O.A.C. chick unit, established by the Association of Official Agricultural Chemists, was a measure of the animal-type vitamin D and was based on the antirachitic response of the chick to the U.S.P. reference cod-liver oil. Vitamin D_3, according to these measures, had a biological efficacy of 45 million I.U. or U.S.P. units per gram, or 58 million A.O.A.C. chick units (36).

Vitamin D is sold in "Standard Units," one Standard Unit being equal to one million U.S.P. units.

There is only one **physical method** for the determination of vitamin D, the measurement of the characteristic *absorption spectrum* in the ultraviolet (at 265 mμ). This method is fairly accurate in the absence of other substances with absorption in the same region. Such interfering substances can be removed from concentrates of vitamin D derived from fish oils or from irradiation procedures provided they contain at least 50,000 I.U. per gram (11).

Among the **chemical methods** proposed for the quantitative assay of vitamin D, the antimony trichloride color reaction has received greatest attention (9). When interfering compounds are removed, the extinction at 550 mμ of the color produced by the reagent can be determined with as little as 0.02–0.4 mg. vitamin D. The higher the concentration the more accurate an estimation can be given (12,25). A similar situation exists when glycerol dichlorohydrin is used to produce a color that can be measured quantitatively (10,31).

Neither the physical nor the chemical methods available or proposed are sufficiently accurate to determine vitamin D in low concentration. Furthermore, all of these procedures fail to differentiate between the various forms of vitamin D, an analytical procedure which is most important from a commercial point of view. The only satisfactory method of analysis is the **biological method,** which, however, is costly, time-consuming, and accurate only within the limits of the biological assay. Rats and chicks are used as test animals for vitamin D preparations. All preparations to be analyzed or standardized are first assayed with rats. The official method of the *U.S. Pharmacopeia* uses the curative procedure (33). Weanling rats are placed on a rachitogenic diet and different levels of the unknown are fed to some animals while others receive known amounts of a reference standard. The criterion of healing is the development of a line of new calcification through the rachitic metaphysis, made visible by staining with silver nitrate. After the potency of a preparation for rats is established, a chick assay may be performed. According to the procedure of the Association of Official Agricultural Chemists the potency is determined on the basis of the percentage of ash in the tibia (2). The potency is calculated on the basis of statistical treatment of the data (37).

BIOLOGICAL FUNCTIONS AND VITAMIN D DEFICIENCY

In the broadest aspect, vitamin D stimulates growth. The most obvious symptom of this action is the effect of vitamin D on bone growth. The clinical picture of a vitamin D deficiency is known as *rickets*, which is characterized by a disturbance in the deposition of calcium and phosphorus in the growing bones. This deposition may be retarded or stopped, thus retarding or stopping the growth of bones. Furthermore,

the inorganic material previously deposited may be withdrawn from the bones, causing a considerable softening. An early symptom of a vitamin D deficiency is a lowered phosphorus content in the blood serum. Later a lowering of the calcium level is observed also.

Vitamin D deficiency results in typical skeletal changes which are noticeable in the ribs, forearms, wrists, and legs. In babies the retardation of the calcification of the fontanelles is especially characteristic. Instead of calcification of the bones, excessive cartilage formation sets in, especially at the ends of the long bones, and results in enlargements of the joints. Curvature of the affected bones occurs in later stages of the disease and is especially significant in the limbs, the spine, etc. Deficiency of vitamin D is also a contributing factor in the occurrence of dental caries. Deficiency of vitamin D in children may be the cause of *infantile tetany,* which is usually the sign of the beginning of healing, and occurs when the faulty phosphorus metabolism is relieved while the calcium metabolism is still impaired. Rickets of the adult is known as *osteomalacia* and is characterized by a decalcification of the bones which leads to brittleness.

Vitamin D deficiency, however, does not affect the bones exclusively but the entire body. Besides the changes in the bones, the effects on muscles are most obvious. During severe cases of rickets the muscles become weak and flabby.

Insufficient supply of Vitamin D is equally hazardous to all animals. Of great economic importance is the result of vitamin D deficiency in livestock. Chicks and turkey poults are very sensitive to vitamin D deprivation and soon become inactive and apathetic, with ruffled feathers and awkward gait. Deformities of the breast bone are observed and the long bones break with little resistance. Also the bones in their feet and legs will not support their bodies and bend easily. This is also the case in pigs and calves. Eggs from hens that obtained suboptimal doses of this vitamin have thin shells and do not hatch normally. The egg production declines also as a result of vitamin D deficiency. Vitamin D is equally essential for maintenance, reproduction, and lactation of mature dairy animals.

Requirements. Because of the tremendous importance of vitamin D for growth and maintenance of good health, the requirements for men as well as for farm animals have been studied extensively. The National Academy of Sciences, National Research Council, has issued certain recommendations for dietary allowances for the maintenance of good nutrition in healthy persons in the U.S. According to the 1953 revision, as reported by the Food and Nutrition Board, the vitamin D requirement for optimum health is estimated to be about 400 units per day, regardless of age. This amount of vitamin D will afford ample protection from rickets, provided a sufficient amount of the other essential nutrients, including calcium and phosphorus, is supplied. On the other hand, in order to cure rickets in infants a daily dose of 500–1500 units is usually given (21).

The nutrient requirements of domestic animals have been reviewed by various subcommittees of the Committee on Animal Nutrition. For starting and growing chickens 90 I.C.U. and for laying and breeding hens 225 I.C.U. per pound of feed have been recommended (20). For turkeys 400 I.C.U. per pound of feed has been suggested, without distinction as to age. Starting and growing ducks are believed to require about 100 I.C.U. in each pound of feed. The requirement of swine is about 90 units of vitamin D per pound of feed (19). For sheep (23) and calves (22) about 300 units of vitamin D per 100 pounds of body weight is recommended. Four-footed animals

can get along on vitamin D_2 while poultry must have vitamin D_3. Also for fish, vitamin D_3 apparently is more effective than vitamin D_2 (18).

Toxicity. Like all the other vitamins, vitamin D when given in excessive amounts is toxic. The toxic dose, however, is not clearly defined, apparently because the toxic threshold varies considerably among individuals. As an average figure, a continued daily dose of about 20,000 I.U. of vitamin D per kilogram of body weight has been considered to cause intoxication in man and in dogs. Clinically, however, in the so-called shock therapy, single doses up to 1 million I.U. of the pure crystalline vitamin D dissolved in a suitable medium have been used.

As a result of excessive vitamin D administration the calcium of the bones is mobilized. The calcium content of the serum is increased, decalcification of the skeletal bones sets in, and calcification occurs in various organs and tissues, especially in the kidneys, lungs, heart, blood vessels, and bronchi.

USES

The vitamins D are commercially available in various forms which differ according to the use to be made of the vitamin. In the pharmaceutical industry fish oils have been used for a long time. Cod-liver oil has been a favorite among the low-potency oils, and highly potent percomorph liver oil has enjoyed a specialty market. As supplements for animal feeds "A and D feeding oils" are traded, preparations which are often fortified with manufactured vitamin D_3.

Vitamin D_3 has rapidly captured a good share of the total vitamin D market since it is equally active for man and all animals. The pure crystalline vitamin is used for medicinal preparations, concentrates for the pharmaceutical industry, and the fortification of fresh and evaporated milk. For poultry feeds, special dry vitamin D_3 preparations are produced in which a highly potent vitamin D_3 concentrate in a vegetable oil is dispersed on a dry carrier such as corn or flour. Dry preparations of either 1500 or 3000 units per gram potency are marketed. A vitamin D_3-containing oil–water emulsion is also available for either human or animal use and is valued as a specialty because vitamin D is somewhat more easily absorbed from an emulsion than from an oil solution.

Vitamin D_2 either in crystalline form or as a concentrate in oil is used in some pharmaceutical preparations although vitamin D_3 is now preferred by many authorities as the natural vitamin D of man and animals. Vitamin D_2 in the form of irradiated yeast is manufactured as a feed supplement for cattle, swine, and dogs.

Bibliography

(1) Commission for the Reform of Nomenclature in Biological Chemistry of the International Union of Pure and Applied Chemistry, *J. Chem. Soc.*, **1951**, 3526; *Bull. soc. chim. biol.*, **33**, 1663 (1951).
(2) A.O.A.C., *Methods of Analysis*, 7th ed., 1950, p. 792.
(3) Bergmann, W., "Sterols," *Progr. Chem. Fats, Other Lipids*, **1**, 36 (1952).
(4) Bergmann, W., Lyon, A. M., and McLean, M. J., *J. Org. Chem.*, **9**, 290 (1944).
(5) Bills, C. E., and Honeywell, E. M., *J. Biol. Chem.*, **80**, 15 (1928).
(6) Bills, C. E., in Sebrell and Harris, *The Vitamins*, Academic Press, N.Y., 1954, Vol. II, p. 132.
(7) Bock, R., and Wetter, F., *Z. physiol. Chem.*, **256**, 33 (1938).
(8) Boer, A. G., Reerink, E. H., van Wijk, A., and Niekerk, J., *Proc. Acad. Sci. Amsterdam*, **39**, 622 (1936).
(9) Brockmann, H., and Chen, Y. H., *Z. Physiol. Chem.*, **241**, 129 (1936).
(10) Campbell, J. A., *Anal. Chem.*, **20**, 766 (1948).

(11) Ewing, D. T., Powell, M. J., Brown, R. A., and Emmett, A. D., *Anal. Chem.*, **20,** 317 (1948).
(12) Ewing, D. T., Kingsley, G. V., Brown, R. A., and Emmett, A. D., *Ind. Eng. Chem., Anal. Ed.*, **15,** 301 (1943).
(13) Hickman, K. C. D., and Gray, E. L., *Ind. Eng. Chem.*, **30,** 796 (1938).
(14) Hogness, T. R., Sidwell, A. E., Jr., and Zscheile, F. P., Jr., *J. Biol. Chem.*, **120,** 239 (1937).
(15) Kind, C. A., and Herman, S. C., *J. Org. Chem.*, **13,** 867 (1948).
(16) Linsert, O., *Z. physiol. Chem.*, **241,** 125 (1936).
(17) Matsumoto, T., and Toyama, Y., *J. Chem. Soc. Japan*, **64,** 326 (1943).
(18) McLaren, B. A., Keller, E., O'Donnell, D. J., and Elvehjem, C. A., *Arch. Biochem.*, **15,** 169 (1947).
(19) National Research Council, *Nutrient Requirements for Swine* (Pub. No. 295), rev. 1953.
(20) National Research Council, *Nutrient Requirements for Poultry* (Pub. No. 301), rev. 1954.
(21) National Research Council, *Recommended Dietary Allowances* (Pub. No. 302), rev. 1953.
(22) National Research Council, *Report No. 4 of Recommended Nutrient Allowances for Beef Cattle*, 1951.
(23) National Research Council, *Report No. 5 of Recommended Nutrient Allowances for Sheep*, 1949.
(24) Nelson, E. M., *J. Assoc. Offic. Agr. Chemists*, **32,** 801 (1949).
(25) Nield, C. H., Russell, W. C., and Zimmerli, A., *J. Biol. Chem.*, **136,** 73 (1940).
(26) Petering, H. G., and Waddell, J., *J. Biol. Chem.*, **191,** 765 (1951).
(27) Raoul, Y., Le Boulch, N., Chopin, J., Meunier, P., and Guerillot-Vinet, A., *Compt. rend.*, **235,** 1439 (1952).
(27a) Rosenberg, H. R., *Arch. Biochem. Biophys.*, **42,** 7 (1953).
(28) Rosenberg, H. R., and Waddell, J., *J. Biol. Chem.*, **191,** 757 (1951).
(29) Ruigh, W. L., *J. Am. Chem. Soc.*, **64,** 1900 (1942).
(30) Ruiz, A. S., *An. real acad. farm.*, **3,** 201 (1943).
(31) Sobel, A. E., Mayer, A. M., and Kramer, B., *Ind. Eng. Chem., Anal. Ed.*, **17,** 160 (1945).
(32) Toyama, Y., Kita, M., and Tanaka, T., *Bull. Chem. Soc. Japan*, **25,** 355 (1952); Rosenberg, H. R., *Arch. Biochem. Biophys.*, **56,** 256 (1955).
(33) U.S.P. XV, 1955.
(34) Vliet, J., van der, *Rec. trav. chim.*, **67,** 246, 265 (1948).
(35) Velluz, L., Amiard, G., and Petit, A., *Bull. soc. chim. France*, **16,** 501 (1949).
(36) Waddell, J., and Kennedy, G. H., *J. Assoc. Offic. Agr. Chemists*, **30,** 190 (1947).
(37) Waddell, J., and Kennedy, G. H., *Biol. Symposia*, **12,** 452 (1947).
(38) Windaus, A., and Buchholz, K., *Ber.*, **71,** 576 (1938); **72,** 597 (1939).
(39) Windaus, A., and Langer, R., *Ann.*, **508,** 105 (1933).
(40) Windaus, A., and Trautman, G., *Z. physiol. Chem.*, **247,** 185 (1937).
(41) Windaus, A., Lüttringhaus, A., and Busse, P., *Nachr. Ges. Wiss. Göttingen, Math. physik. Kl. Fachgruppe*, III, 150 (1932).
(42) Windaus, A., Deppe, M., and Wunderlich, W., *Ann.*, **533,** 118 (1937); Setz, P., *Z. physiol. Chem.*, **215,** 183 (1933).
(43) World Health Organization, Expert Comm. on Biological Standardization, *Report of the Subcommittee on Fat-Soluble Vitamins*, 1949; WHO/BS/65 Rev. 1; Chron. WHO 3, 147.
(44) Wunderlich, W., *Z. physiol. Chem.*, **241,** 116 (1936).
(45) U.S. Pat. 1,893,317 (Jan. 3, 1933), A. Zimmerli (to Acetol Products).
(46) U.S. Pat. 2,030,377 (Feb. 11, 1936), O. Linsert (to Winthrop).
(47) U.S. Pat. 2,056,992 (Oct. 13, 1936), J. Waddell (to Du Pont).
(48) U.S. Pat. 2,098,984 (Nov. 16, 1937), A. Windaus and F. Schenck (to Winthrop).
(49) U.S. Pat. 2,099,550 (Nov. 16, 1937), A. Windaus and F. Schenck (to Winthrop).
(50) U.S. Pat. 2,163,659 (June 27, 1939), A. G. Boer, J. van Niekerk, E. H. Reerink, and A. van Wijk (to N. V. Philips' Gloeilampenfabriken).
(51) U.S. Pat. 2,209,934 (July 30, 1940), H. R. Rosenberg (to Du Pont).
(52) U.S. Pat. 2,215,727 (Sept. 24, 1940), H. R. Rosenberg and J. M. Tinker (to Du Pont).
(53) U.S. Pat. 2,255,815 (Sept. 16, 1941), H. R. Rosenberg and T. J. Parsons (to Du Pont).
(54) U.S. Pat. 2,266,674 (Dec. 16, 1941), A. G. Boer, J. van Niekerk, E. H. Reerink, and A. van Wijk (to Hartford National Bank and Trust Co.).
(55) U.S. Pat. 2,369,918 (Feb. 20, 1945), H. R. Rosenberg (to Du Pont).
(56) U.S. Pat. 2,376,817 (May 22, 1945), H. R. Rosenberg (to Du Pont).
(57) U.S. Pat. 2,383,446 (Aug. 28, 1945), W. S. Calcott, J. Waddell, and H. R. Rosenberg (to Du Pont).

(58) U.S. Pat. 2,386,635 (Oct. 9, 1945), H. R. Rosenberg (to Du Pont).
(59) U.S. Pat. 2,436,195 (Feb. 17, 1948), J. A. Callan (to Du Pont).
(60) U.S. Pat. 2,441,091 (May 4, 1948), J. van der Vliet and W. Stevens (to Hartford National Bank and Trust Co.).
(61) U.S. Pat. 2,505,646 (April 25, 1950), W. C. Meuly (to Du Pont).

GENERAL REFERENCES

(62) Association of Vitamin Chemists, *Methods of Vitamin Assay*, 2nd ed., Interscience, N.Y.-London, 1951, pp. 267–72.
(63) Bergmann, W., "Sterols," *Progr. Chem. Fats, Other Lipids*, **1**, 18 (1952).
(64) György, P., *Vitamin Methods*, Academic Press, N.Y., 1951, Vol. II.
(65) Reed, C. I., Struck, H. C., and Steck, I. E., *Vitamin D*, Univ. Chicago Press, 1939.
(66) Rosenberg, H. R., *Chemistry and Physiology of the Vitamins*, rev. reprint, Interscience, N.Y.-London, 1945, pp. 341–432.
(67) Sebrell, W. H., Jr., and Harris, R. S., *The Vitamins, Chemistry, Physiology, Pathology*, Academic Press, N.Y., 1954, Vol. II, Ch. 6.

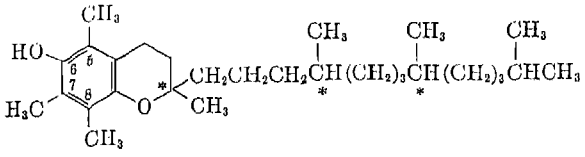
H. R. ROSENBERG

VITAMIN E

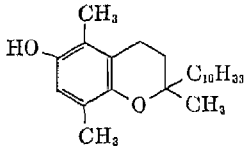
The term "vitamin E" was used originally to describe a partially characterized material in vegetable oils that was essential for the rat to maintain fertility. Discovery of this new fat-soluble vitamin in 1922, and early pioneer investigations of its natural distribution, isolation, and identification were due primarily to Evans, Burr, and Emerson of the University of California, and Mattill and Olcott of the University of Iowa. More than one naturally occurring substance and a variety of apparently unrelated organic compounds were found subsequently that acted like vitamin E in the body. Also, the symptoms of vitamin E deprivation were discovered to be very different in different species of animals. Consequently, "vitamin E potency" was used for many years to designate, in a general manner, a type of physiological activity that could cure or prevent any vitamin E-deficiency symptom in animals.

Isolation and identification of four naturally occurring compounds possessing vitamin E activity were finally achieved, and these substances were designated α-, β-, γ-, and δ-**tocopherols** (I–IV; * denotes points of asymmetry). (Tocopherol is derived from Greek words meaning to bring forth offspring and is pronounced tō-kŏf-ēr-ōl.) Although the tocopherols are closely related chemically, all being methyl derivatives of *tocol* (2-methyl-2-(4,8,12-trimethyltridecyl)-6-chromanol), they have quite different biological potencies. α-Tocopherol, with a completely methylated aromatic ring, is the most potent. Because of its high potency, which makes it the preferred form for clinical use, and because, as α-tocopheryl acetate, it has been universally recognized as the International Standard of Vitamin E since 1941, the term "α-tocopherol" is now widely used instead of "vitamin E." The latter term is reserved as a group name for preparations possessing α-tocopherol-like physiological activity.

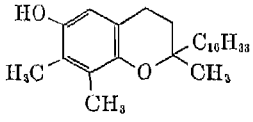
Both α-tocopherol and α-tocopheryl acetate, the forms most used commercially, are clear, slightly yellow oils, odorless, and quite viscous. The naturally occurring dextro form is the most active isomer, physiologically; the synthetic *dl*-α-tocopherol and its esters have about 70–75% the potency of the corresponding dextro forms. The principal commercial uses of α-tocopherol are in medicine and in livestock feeding as a source of vitamin E activity and in food technology and pharmacy as an antioxidant to retard the development of rancidity in fatty materials.



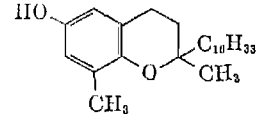
(I) α-Tocopherol (5,7,8-trimethyltocol)



(II) β-Tocopherol
(5,8-dimethyltocol)



(III) γ-Tocopherol
(7,8-dimethyltocol)



(IV) δ-Tocopherol
(8-methyltocol)

PROPERTIES

The physical property of **α-tocopherol,** $C_{29}H_{50}O_2$, formula weight 430.69, of most commercial interest is its fat solubility. Both α-tocopherol and α-tocopheryl acetate are freely soluble in glyceride oils, alcohol, chloroform, and acetone. They are insoluble in water.

The optical activity of natural *dextro*-α-tocopherol is very slight. For *dextro*-α-tocopheryl acetate the optical rotation of a 10% solution in chloroform in a 200-mm. tube is only +0.25°.

A few physical properties of commercial vitamin E products are shown in Table I; these are taken from monographs (5) proposed for the 10th edition of the National Formulary. Another important product, especially for tablets and dry-fill capsules, is *dextro*-α-tocopheryl acid succinate, a crystalline solid, m.p. 76–77°C.

TABLE I. Some Physical Properties of Commercial Vitamin E Products.

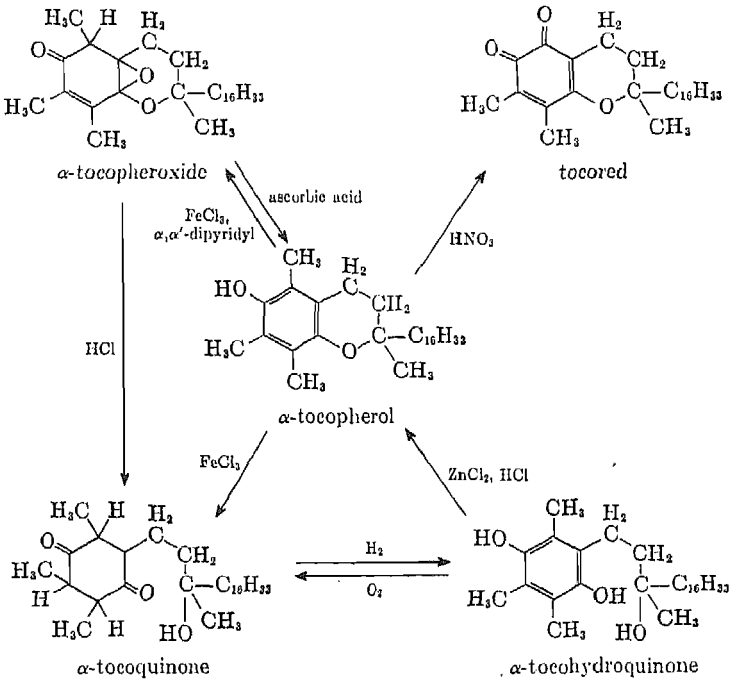
Vitamin E product	Sp.gr.$^{25}_{25°C.}$	n_D^{25}	E(1%,1 cm.) in ethyl alcohol
dextro-α-Tocopheryl acetate; melts about 25°C.	0.950–0.964	1.4940–1.4985	40–44 at 284 mμ
dextro-α-Tocopheryl acetate concentrate; contains at least 25% *dextro*-α-tocopheryl acetate (liquid)	0.932–0.955	[a]	[a]
Mixed tocopherols concentrate; contains at least 34% total tocopherol; at least half of tocopherols is *dextro*-α-tocopherol (liquid)	0.932–0.955	[a]	[a]
dl-α-Tocopherol (liquid)	0.947–0.958	1.5030–1.5070	71–76 at 292 mμ
dl-α-Tocopheryl acetate (liquid)	0.950–0.964	1.4940–1.4985	40–44 at 284 mμ

[a] Varies with potency of concentrate.

In addition to light-catalyzed oxidation of α-tocopherol, destruction is also accelerated by unsaturated fatty acid oxidation, and the presence of metal salts and alkalies. Oxidation proceeds according to reactions shown in Scheme 1. Further oxidation (chromic acid) yields dimethylmaleic anhydride, biacetyl, acetone, a C_{16}-acid, a C_{18}-ketone, and a C_{21}-lactone. From these products, Fernholz (8) in 1938 correctly postulated the structure of α-tocopherol.

The ready reversibility of α-tocopherol with certain of its oxidation products suggests that vitamin E acts in the body as an integral part of some oxidation-reduction system or enzyme. The existence of a free semiquinone radical of α-tocopherol has been demonstrated by Michaelis by ultraviolet irradiation at low temperatures (16). It might well be the critical factor in one or more vital oxidation-reduction reactions *in vivo*.

SCHEME I



α-Tocohydroquinone (α-tocopherol hydroquinone) shows good activity in preventing and curing muscle dystrophy in hamsters, while *α-tocoquinone* (α-tocopherol quinone) as well as α-tocohydroquinone is effective in the rabbit. The rat can utilize *α-tocopheroxide* (α-tocopherol epoxide) to a slight degree for preserving reproductive function, but further oxidized products are ineffective.

Esterification of α-tocopherol ordinarily does not affect the biological activity, but etherification almost completely eliminates biopotency. Other derivatives of α-tocopherol in which ring methyl groups are substituted or in which the phytyl side chain is modified all show lowered potency.

OCCURRENCE

Cereal grain oils contain the highest concentration of tocopherol of any foodstuff commonly eaten by animals including humans. Crude cottonseed, corn, and soybean oils contain 100–200 mg. of tocopherol/100 g. prior to refining. The amount of tocopherol left in refined salad oil is dependent upon the severity of the refining process.

Certain vegetable oils are exceptions to the general rule that such oils are rich in tocopherol content. For example, coconut and olive oils are practically devoid of

tocopherol. Also, refined corn oil and soybean oil, although they possess a large total tocopherol content, have only about 7–10 mg. α-tocopherol/100 g. Most of the tocopherols in corn and soybean oils are the relatively low-potency non-α-tocopherols. The γ-form predominates in corn; the γ- and δ-forms in soybean oil.

The major portion of the approximately 14 mg. estimated mean daily intake of α-tocopherol of the average person in the U.S. is derived from margarine, salad oils, and shortening. Other foods supply relatively little of the α-tocopherol ingested, as shown in Table II (11,24). Farm animals receive most of their α-tocopherol from fresh grains and alfalfa leaf meal and, of course, fresh grasses if the animals have pasture available. Dairy products and meats are poor food sources of tocopherol and also highly variable in their content of this vitamin. The amount of tocopherol in eggs, milk, or beefsteak is dependent upon the amount of α-tocopherol received by the animal from which these products were obtained.

Losses of α-tocopherol during the processing of foods and during cooking have not been investigated very extensively. However, high-energy gamma radiation, from Co^{60} for example, during food sterilization does result in considerable α-tocopherol destruction. Losses of about 60% in milk on 6 hours' exposure to 80,000 r./hr. have been reported (14). Also, deep-fat cooking of doughnuts and scallops results in 50–90% destruction of α-tocopherol.

Flour from wheat and other cereal grains treated with benzoyl peroxide, chlorine dioxide, Agene (NCl_3), and other bleaching and aging chemicals, have been reported to suffer significant losses of α-tocopherol (11).

TABLE II. Estimate of Mean Per Capita α-Tocopherol Intake Based on U.S.D.A. Values for Food Consumption.

Commodity	Food consumed		α-Tocopherol intake, mg./day
	Amount, g./day	α-Tocopherol concn., mg./100 g.	
Fats and oils	81		7.87
Butter, lard, etc., 53 g.		0.5–3	
Shortening, margarine, etc., 28 g.		7–70	
Grain products	213	0.3–2	1.78
Meat, poultry, and fish	196	0.2–1	0.99
Potatoes and sweet potatoes	143	0.1–4	0.84
Eggs	58	0.5–1	0.68
Dairy products	536	0.1–1	0.58
Green leafy and yellow vegetables	142	0.1–0.5	0.50
Dried peas, beans, and nuts	20	0.1–4	0.43
Citrus fruits and tomatoes	131	0.2–0.4	0.35
Other vegetables and fruits	291	0.1–0.5	0.12
Coffee, tea, and cocoa	24	0–2	0.06
Sugar and sirups	132	0	0.00
			14.20

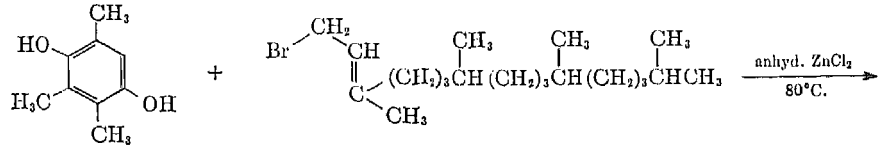
ISOLATION AND SYNTHESIS

The naturally occurring *dextro*-tocopherols are produced from vegetable oil sources. An important step, technically, is the concentration by molecular distillation (6) (see also *Distillation*, Vol. **5,** p. 185). For example, alkali-refined soybean oil (see Vol. **12,** p. 696), containing 0.19% of a mixture of α-, γ-, and δ-tocopherols, is distilled in a centrifugal-type molecular still and the tocopherol fraction, which dis-

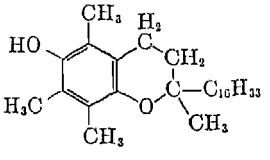
tills below 240°C. under 0.004 mm. pressure, is collected. After removal of as much of the sterols and other crystallizable substances as possible by crystallization from acetone at −10°C. and removal of glycerides by saponification, the tocopherols in the unsaponifiable matter are further concentrated by molecular distillation. Thus a fraction containing at least 60% mixed tocopherols is obtained (22).

The four tocopherols have been synthesized in their *dl*-form, and one, *dl*-α-tocopherol, is produced commercially by synthesis. Although details of the commercial methods have not been published, it is understood that the process follows closely the procedures used in the first syntheses of α-tocopherol in 1938. Almost simultaneously, Karrer, Fritzsche, Ringier, and Salomon of Zürich (12), Bergel, Jacob, Todd, and Work of Manchester (1), and Smith, Ungnade, and Prichard of Minnesota (21) reported the synthesis of racemic α-tocopherol. According to these authors, trimethylhydroquinone is condensed with phytol (1) (see Vol. **13,** p. 757), phytyl halide (12), or phytadiene (21). The condensation can be carried out in benzene or similar nonreactive solvents in the presence or absence of certain catalysts such as zinc chloride or formic acid. Acetic acid has also been used successfully as a solvent in this synthesis. The reaction used by Karrer *et al.* (25) is shown in Scheme 2.

SCHEME 2



trimethylhydroquinone phytyl bromide



α-tocopherol

The *dl*-forms of β-, γ-, and δ-tocopherols can be synthesized by the procedures used for the synthesis of *dl*-α-tocopherol. Instead of trimethylhydroquinone the appropriate di- or monomethylhydroquinone is used. Thus *p*-xylohydroquinone yields *dl*-β-tocopherol, *o*-xylohydroquinone yields *dl*-γ-tocopherol, and toluhydroquinone yields *dl*-δ-tocopherol. The yields of these compounds are usually less than that obtained in the synthesis of α-tocopherol since the hydroquinones can condense with more than one molecule of phytol. An improvement is achieved by the use of monoesters, such as the monobenzoates, of the hydroquinones.

A number of other synthetic procedures have been used for the synthesis of tocol homologs and analogs (33). Esters of the tocopherols are readily prepared. Typical laboratory procedures for the acetate (19a), the succinate (20a), and the phosphate (11a) have been described.

Economics. No statistics are available on the production of either the natural or the synthetic preparations of vitamin E which are on the market. The changes in bulk price of the α-tocopheryl acetates from 1944 to 1954 are shown in Table III. A

price reduction, effective in October 1954, resulted in a price of $136 per million units for both types or, on a per kilo basis, $185 for the dextro form and $136 for the less active *dl*-form.

TABLE III. Price of α-Tocopheryl Acetate in Bulk ($/Kg.).

	1944–47	1947–50	1950–52	1953	1954
dextro-α-Tocopheryl acetate	—	250	250	225	185
dl-α-Tocopheryl acetate	1000	750	350	225	136

Specifications and standards for various tocopherol preparations intended for pharmaceutical use are listed in the proposed monographs (5) for N.F. X (see also Table I). They may be labeled in terms of *mg. of dextro- or dl-α-tocopherol* or *α-tocopheryl acetate*, as the case may be, or in *International Units*.

Label claims for tocopherol preparations when expressed in International Units are based on the following equivalents:

1 mg. *dl*-α-tocopheryl acetate	= 1.0	International	Unit
1 mg. *dl*-α-tocopherol	= 1.1	"	"
1 mg. *dextro*-α-tocopheryl acetate	= 1.36	"	"
1 mg. *dextro*-α-tocopherol	= 1.49	"	"

ASSAY

Chemical and Physical Methods. The methods of analysis for pure or highly concentrated free α-tocopherol preparations are rather simple. Reaction with the *Emmerie-Engel* reagent (α,α′-dipyridyl (2,2′-bipyridine) and ferric chloride) gives a red color from combination of the dipyridyl with the ferrous ions resulting from reduction of the ferric ions; this color is directly proportional to the amount of tocopherol present. Titration with ceric sulfate is a good alternative procedure for pure forms. Using diphenylamine as indicator, α-tocopherol in 0.5 *N* alcoholic sulfuric acid is titrated with 0.01 *N* ceric sulfate to a blue end point. Spectrophotometric measurement is sometimes used, based on the measurement of the specific absorbancy, which is proportional to α-tocopherol concentration.

Analysis of lower-potency concentrates, original vegetable oils, or foods and feeds is considerably more difficult. The Emmerie-Engel color reaction is nonspecific. Hence many nontocopherol reducing materials soluble in alcohol obtained along with the α-tocopherol in the original extract from foods must be removed before the reaction is applied. Extraneous reducing materials of this nature including vitamin A and carotenoids also interfere in other chemical and physical-chemical methods of analysis. Molecular distillation, acid washing, hydrogenation, and chromatography may be used for making these separations and yielding a concentrate of tocopherols adequately purified for colorimetric assay (19).

If an estimate of "total tocopherol" content is not satisfactory, further analysis must be done to obtain the "α-tocopherol" content. Nitrosation (18) or coupling with diazotized dianisidine (3,3′-dimethoxybenzidine) (17) permits measurement of the non-α-tocopherols. The α-tocopherol content may then be calculated by difference. However, a more desirable approach for future study would be a direct analysis for α-tocopherol, such as that described by Brown (3), in which paper chromatography is used to separate the individual tocopherols. α-Tocopherol is eluted from a paper chromatogram and measured colorimetrically or spectrophotometrically.

Analysis of a tocopherol ester requires an initial hydrolysis before any colorimetric analysis is applied. This step is extremely critical because of the sensitivity of tocopherols to destruction by alkalies. However, if sufficient care is taken to rigorously exclude oxygen from the system or to add an effective antioxidant (23), saponification may be conducted without loss of tocopherol.

The usual **bioassay** procedure for determining α-tocopherol activity is a modification of the Evans resorption gestation method (1a,7,15). Female rats are raised on a vitamin E-free diet and mated with normal males. Conception and the first half of pregnancy are normal. However, unless a vitamin E supplement is administered during the first 10–12 days of pregnancy, the embryos die and are resorbed. The mother rat is apparently unharmed and may be used repeatedly. If the dose of α-tocopherol administered as a test supplement is above a certain critical amount, pregnancy proceeds and terminates normally. The critical dose of α-tocopherol varies somewhat between assays, 0.3–1.0 mg., but the response is an all-or-none type, the young are either alive or dead, a criterion which is easily determined. Consequently, the bioassay properly controlled and carefully conducted is accurate and reasonably precise.

Another bioassay procedure based upon a different physiological response has been described by Rose and György (20). Adult rats receiving adequate vitamin E in their diet have red blood cells that are resistant to hemolysis induced by chemical action of such compounds as alloxan and hydrogen peroxide. Changing the animals to a vitamin E-deficient diet for several days causes the red blood cells to become susceptible to hemolysis. A satisfactory bioassay constitutes the administration of various levels of α-tocopherol (both standard and test substance), either prophylactically or curatively, to the rats during the depletion period and measurement of the change in degree of red cell hemolysis that results.

BIOCHEMICAL FUNCTION AND CLINICAL EVALUATION

The exact mechanism whereby α-tocopherol functions in the body as vitamin E is unknown. It undoubtedly acts as an antioxidant controlling redox reactions in a variety of tissues and organs. Also, as indicated by the high specificity of the α-tocopherol structure in physiological reactions, this tocopherol may occur as an integral part of an enzyme or function as a co-enzyme. Oxidations catalyzed by hemin, hemoglobin, and cytochrome c *in vitro* are inhibited by α-tocopherol, and similar control may occur *in vivo*.

Experiments with vitamin E-deficient animals have shown that α-tocopherol plays some role in the maintenance of normal muscle and collagen tissues, of a sound vascular system, and of red blood cells resistant to hemolysis. The gross and microscopic pathology which results in the tissues and organs of various species of vitamin E-deficient animals has been described by Mason (29,30). In the very young and very old rat, the guinea pig, rabbit, and hamster, hyaline degeneration of the skeletal and cardiac muscles is a characteristic deficiency symptom and leads to muscular incoordination and eventual death. In rats and chicks, structural or functional changes occur in the vascular system during vitamin E deprivation, leading to edema or fatal hemorrhages. The effects of α-tocopherol administration in increasing the resistance of red blood cells to chemically induced hemolysis have been reported in rats by Rose and György (20) and in human infants by Gordon *et al.* (9) and György *et al.* (10).

Subnormal reproductive functions in both males and females were some of the clinical symptoms first treated with α-tocopherol. Results have been conflicting

and further controlled experimental work should be done to define those specific types of reproductive trouble for which vitamin E therapy may be recommended. The broad group of diseases of collagen tissue, the so-called collagenoses, have been treated empirically with vitamin E. The results indicate that α-tocopherol treatment does have value and brings relief in such conditions as lupus erythematosus, primary fibrositis, Dupuytren's contracture, and Peyronie's disease. The value of α-tocopherol administration to patients with cardiovascular diseases is still a matter of clinical controversy. Proponents have reported that all cardiovascular syndromes are cured by vitamin E if proper doses are given. The underlying abnormality which is rectified by α-tocopherol seems to be localized tissue anoxia due to vascular stasis or decreased oxygen-carrying capacity of the blood. α-Tocopherol somehow enables oxygen to be more efficiently utilized *in vivo*. The concept of the effect of α-tocopherol on vascularity receives some experimental support from clinical studies that show that it relieves menopausal tension (13) and the pain of intermittent claudication (2).

In pediatrics, some consideration is being given to the possible need of newborn infants for α-tocopherol supplementation. Infants, particularly prematures, are poorly supplied with vitamin E because the placenta acts as a barrier preventing the passage of α-tocopherol from the mother to the fetus. Conversely, early milk is very rich in tocopherol content, apparently designed to supply infants relatively large amounts of vitamin E early in life. Artificial feeding with formulas based on cows' milk supplies very little α-tocopherol, but such infant feeding preparations could be fortified with vitamin E up to the level in human milk. Also, in pediatric practice, therapeutic-sized doses of α-tocopherol have been used to treat symptoms characterized by edema and capillary hemorrhage, and to increase the relatively low resistance of infants' red blood cells against hemolysis.

α-Tocopherol administered orally in massive doses is well tolerated, and no symptoms of toxicity have been reported. Mice fed as much as 40 g. α-tocopherol per kg. body weight and rats 4 g. per kg. for several weeks showed no deleterious effects (4). Parenteral administration of α-tocopherol as an oil concentrate or in ethyl laurate, or as the phosphate ester, is not recommended. Local reactions at the site of injection are common, and utilization of the injected tocopherol is very poor.

USES

The use of α-tocopherol and α-tocopherol esters in multivitamin and therapeutic-type capsules takes most of the commercially produced vitamin E. Tocopheryl acid succinate is also used in the formulation of multivitamin tablets and dry-fill capsules. Tocopheryl phosphate and α-tocopherol dispersed in aqueous media find some use as injectable preparations. Also, specialty items such as vitamin E-containing ointments, salves, and suppositories provide other outlets for α-tocopherol in the pharmaceutical field. Doses as prescribed by physicians for human use range from a few milligrams for dietary supplementation to 500–1000 mg. for certain therapeutic applications.

A granular preparation of α-tocopheryl acetate containing about 20,000 I.U. per pound is used in poultry feeds. This same type of preparation is used to some extent for fortifying rations of fur-bearing animals, for calf and lamb supplements, pig concentrates, and turkey laying mashes. The vitamin E naturally present in feedstuffs is relatively unstable in stored, mixed feeds. In order to replace tocopherol that

might have been destroyed, stable α-tocopheryl acetate is added at levels ranging from 5 to 40 grams per ton of feed.

α-Tocopherol as an antioxidant (see Vol. **6**, pp. 839–40) has been used to some extent by food technologists and by pharmaceutical formulators. It is particularly effective in essential oils, rendered animal fats, and mineral oil. In pharmaceutical preparations, α-tocopherol stabilizes other vitamins, especially vitamin A, during shelf-life and also in the gastrointestinal tract. After absorption it is deposited in all tissues and organs of the body. Tocopherol is unique among fat-soluble antioxidants because it is absorbed and deposited in body tissues. In contrast, other antioxidants are destroyed or excreted.

Bibliography

(1) Bergel, F., Jacob, A., Todd, A. R., and Work, T. S., *Nature*, **142**, 36 (1938).
(1a) Bliss, C. I., and György, P., "Animal Vitamin Assays," in György, ed., *Vitamin Methods*, Academic Press, N. Y., 1951, Vol. II, pp. 136–55.
(2) Boyd, A. M., Ratcliffe, A. H., Jepson, R. P., and James, G. W. H., *J. Bone Joint Surg.*, **B31**, 325–55 (1949).
(3) Brown, F., *Biochem. J.*, **52**, 523–26 (1952).
(4) Demole, V., *Intern. Z. Vitaminforsch.*, **8**, 338–41 (1939).
(5) *Drug Standards*, **22**, 95–103 (1954); N. F. X, 1955.
(6) Embree, N. D., *Chem. Revs.*, **29**, 317–32 (1941).
(7) Evans, H. M., and Burr, G. O., *Mem. Univ. Calif.*, **8**, 1–176 (1927).
(8) Fernholz, E., *J. Am. Chem. Soc.*, **60**, 700–5 (1938).
(9) Gordon, H. H., DeMetry, J. P., and Csapo, G., *Am. J. Diseases Children*, **84**, 472–74 (1952).
(10) György, P., Cogan, G., and Rose, C. S., *Proc. Soc. Exptl. Biol. Med.*, **81**, 536–38 (1952).
(11) Harris, P. L., Quaife, M. L., and Swanson, W. J., *J. Nutrition*, **40**, 367–81 (1950).
(11a) Karrer, P., and Bussman, G., *Helv. Chim. Acta*, **23**, 1137–38 (1940).
(12) Karrer, P., Fritzsche, H., Ringier, B. H., and Salomon, H., *Helv. Chim. Acta*, **21**, 520–5 (1938).
(13) Kavinoky, N. R., *Ann. Western Med. Surg.*, **4**, 27–32 (1950).
(14) Kung, H. C., Gaden, E. L., and King, C. G., *Agr. Food Chem.*, **1**, 142–44 (1953).
(15) Mason, K. E., and Harris, P. L., *Biol. Symposia*, **12**, 459–83 (1947).
(16) Michaelis, L., and Wollman, S. H., *Biochim. et Biophys. Acta*, **4**, 156–159 (1950).
(17) Quaife, M. L., *J. Am. Chem. Soc.*, **66**, 308 (1944).
(18) Quaife, M. L., *J. Biol. Chem.*, **175**, 605–17 (1948).
(19) Quaife, M. L., and Harris, P. L., *Anal. Chem.*, **20**, 1221–4 (1948).
(19a) Robeson, C. D., *J. Am. Chem. Soc.*, **64**, 1487 (1942).
(20) Rose, C. S., and György, P., *Proc. Soc. Exptl. Biol. Med.*, **74**, 411–15 (1950).
(20a) Smith, L. I., Renfrow, W. B., and Opie, J. W., *J. Am. Chem. Soc.*, **64**, 1084–86 (1942).
(21) Smith, L. I., Ungnade, H. E., and Prichard, W. W., *Science*, **88**, 37 (1938).
(22) Stern, M. H., Robeson, C. D., Weisler, L., and Baxter, J. G., *J. Am. Chem. Soc.*, **69**, 869–74 (1947).
(23) Swick, R. W., and Baumann, C. A., *Anal. Chem.*, **24**, 758–60 (1952).
(24) U.S. Dept. of Agriculture, *Consumption of Food in the U.S.* 1909–48 (Misc. Publ. 691), 1949.
(25) U.S. Pat. 2,208,585 (July 23, 1940), P. Karrer (to Hoffmann-La Roche).

GENERAL REFERENCES

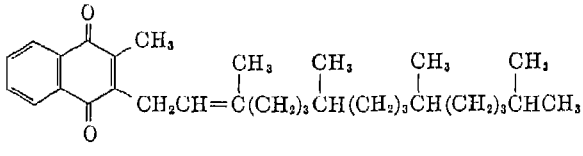
(26) Bicknell, F., and Prescott, F., "Vitamin E (The Antisterility or Antidystrophic Vitamin; Alpha-, Beta-, Gamma- or Delta-Tocopherol)," in *The Vitamins in Medicine*, 3rd ed., Heinemann, London, 1953, pp. 592–670.
(27) Blaxter, K. L., and Brown, F., "Vitamin E in the Nutrition of Farm Animals," *Nutrition Abstr. & Revs.*, **22**, 1–21 (1952).
(28) Lehman, R. L., "Determination of Vitamin E," in Glick (ed.), *Methods of Biochemical Analysis*, Interscience, N.Y.-London, 1955, Vol. 2.

(29) Mason, K. E., "Physiological Action of Vitamin E and Its Homologues," *Vitamins and Hormones*, **2**, 107–53 (1944).
(30) Mason, K. E., Harris, P. L., Harris, R. S., and Mattill, H. A., "The Tocopherols," in Sebrell and Harris, *The Vitamins*, Academic Press, N.Y., 1954, Vol. III, Ch. 17.
(31) Pappenheimer, A. M., "Vitamin E Deficiency," in Cannon, *American Lectures in Pathology*, Charles C Thomas, Springfield, Ill., 1948, Publ. No. 17, pp. 1–33.
(32) Rosenberg, H. R., *Chemistry and Physiology of the Vitamins*, rev. reprint, Interscience, N.Y.-London, 1945, pp. 435–65.
(33) Smith, L. I., *Chem. Revs.*, **27**, 287–329 (1940).
(34) "Vitamin E," *Ann. N.Y. Acad. Sci.*, **52**, 63–427 (1949).

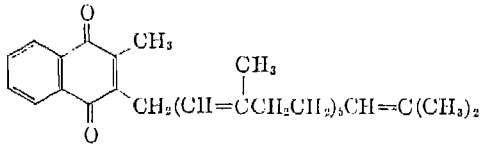
PHILIP L. HARRIS AND NORRIS D. EMBREE

VITAMIN K

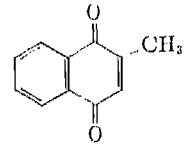
The term "Koagulationsvitamin," from which the name "vitamin K" was derived, was proposed by Dam in 1935 for a fat-soluble dietary factor that had been shown to be essential for the coagulation of blood in the chick. Subsequent work revealed the existence of two natural products having vitamin K activity. Vitamin K_1 is the designation for 2-methyl-3-phytyl-1,4-naphthoquinone (I), the active principle isolated from the green leafy tissues of alfalfa, which occurs also in all other green leaves. Vitamin K_2, which is obtained from putrefied fish meal and which can be found in most bacteria, is the 3-difarnesyl derivative of 2-methyl-1,4-naphthoquinone (II).



(I) Vitamin K_1 (phytonadione)



(II) Vitamin K_2



(III) 2-Methyl-1,4-naphthoquinone (menadione, vitamin K_3)

Today the term "vitamin K" is used somewhat loosely in referring to 2-methyl-1,4-naphthoquinone (menadione) (III) and a number of chemically related compounds that are effective against the hemorrhagic syndrome (see also *Quinones*, Vol. **11**, p. 419).

Vitamin K_1 (commercially available also as a stable emulsion) and menadione, as well as the water-soluble salts menadione sodium bisulfite and the tetrasodium salt of dihydromenadione diphosphate, are commercially important compounds possessing vitamin K activity.

The existence of a vitamin deficiency as a cause of hemorrhage was first suspected in 1929. Dam in the course of study of the metabolism of cholesterol observed that chicks that had been kept on a diet devoid of ether-soluble components developed hemorrhages. McFarlane and his collaborators in 1931 more definitely established the existence of a factor by determining that chicks maintained on fish meal extracted

with ether developed a distinct hemorrhagic tendency which could be cured by feeding unextracted fish meal. In 1936 Schønheyder proposed that the hemorrhagic syndrome resulted from hypoprothrombinemia. The work of Dam and Quick supported this hypothesis.

Vitamin K_1

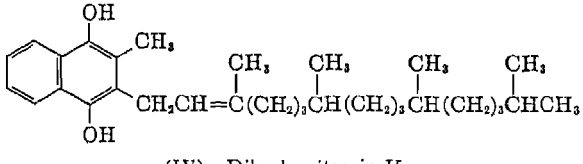
PHYSICAL AND CHEMICAL PROPERTIES

Vitamin K_1 (phytonadione, U.S.P. XV, N.N.R., phylloquinone) (I), $C_{31}H_{46}O_2$, formula weight 450.68, is a mobile yellow oil. It can be crystallized from acetone or ethyl alcohol as yellow rosettes melting at about −20°C. The vitamin is insoluble in water, sparingly soluble in methanol or ethyl alcohol, but it dissolves readily in petroleum ether, benzene, ether, dioxane, chloroform, acetone, and in other fat solvents as well as in vegetable oils. Vitamin K_1, a quinone, is neutral and is stable to air and moisture; thus an ethereal solution of the vitamin can be concentrated to dryness without decomposition at atmospheric pressure on a steam bath, and the vitamin can be distilled without significant decomposition at pressures $\leqq$ 0.001 mm. However, vitamin K_1 is highly sensitive to ultraviolet radiation and even to diffuse daylight, although light radiations between 400 and 800 mμ have no appreciable effect (24). The optical rotation ($[\alpha]_D^{20}$ about −0.4° (benzene)) has been determined on a synthetic sample prepared from natural phytol. The oxidation-reduction potential in 80% alcoholic solution 0.02 *N* in acetic acid and 0.02 *N* in sodium acetate, is 0.005 v. (25°C.) (50); $E_0^{alc.}$ (95% alcohol, 0.2 *N* in hydrochloric acid and 0.02 *N* in lithium chloride) is 0.363 v. (20°C.) (71); and the half-wave potential for reduction at the dropping mercury electrode (isopropyl alcohol and 0.1 *N* aqueous potassium chloride) is −0.58 v. (43). The ultraviolet absorption spectrum of vitamin K_1 has been reported both in hydrocarbon solvents and in methanolic solution (24,44,47). In such solvents as hexane or isooctane (2,2,4-trimethylpentane) vitamin K_1 has a well resolved absorption spectrum with maxima (44,47) at 243–244 mμ (log ε 4.25–4.27), 248–249 mμ (4.28), 261–263 mμ (4.24), 270 mμ (4.24), and 325–328 mμ (3.49–3.50). An additional maximum at 239 mμ has been reported (24).

The infrared absorption spectrum of racemic vitamin K_1 has been published (47). When chromatographed in a 75% (v./v.) aqueous ethyl alcohol solution on Whatman No. 1 filter paper impregnated with silicone, vitamin K_1 had $R_F = 0.20$ (42).

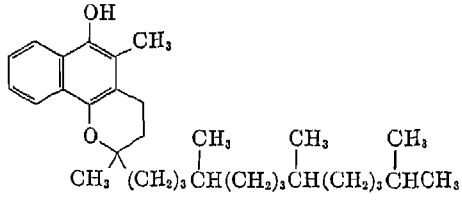
Dilute acids do not affect the vitamin, but alkali readily decomposes it. The reaction of the quinone with alcoholic alkali is the basis of the Dam-Karrer color reaction involving a slow development of a violet-blue coloration which gradually changes into a dull red (26). A small amount of phthiocol (2-hydroxy-3-methyl-1,4-naphthoquinone) is formed in this reaction.

Vitamin K_1 can be reduced to the naphthohydroquinone *dihydrovitamin* K_1 (IV), both by catalytic hydrogenation (47,52) using deactivated palladium catalyst and by



(IV) Dihydrovitamin K_1

sodium hydrosulfite, $Na_2S_2O_4$ (26). The reduction product is a waxy solid insoluble in petroleum ether. It is of considerable importance in the isolation and the purification of the vitamin, since in an ethereal solution it can be reoxidized smoothly to the quinone by shaking with air (8) or, more conveniently, with silver oxide in the presence of magnesium sulfate. Reductive acetylation of vitamin K_1 affords the colorless crystalline dihydrovitamin diacetate, m.p. 62–63°C. (54). Upon refluxing vitamin K_1 in acetic acid with stannous chloride and concentrated hydrochloric acid or with zinc and sulfuric acid, the naphthotocopherol (V) is formed (85). This compound can also be obtained from the dihydrovitamin on boiling in acetic acid containing sulfuric acid. Hydrogenation of vitamin K_1 with Raney nickel in methanol gives 2-methyl-3-β,γ-dihydrophytyl-1,4-naphthohydroquinone ((IV), with a saturated side chain). Finally, reduction of vitamin K_1 in acetic acid in the presence of platinum results in complete hydrogenation to 2-methyl-3-β,γ-dihydrophytyl-5,6,7,8-tetrahydro-1,4-naphthohydroquinone (50).



(V) Naphthotocopherol derived from dihydrovitamin K_1

Oxidation of vitamin K_1 with hydrogen peroxide in an alkaline medium yields the 2,3-epoxide (vitamin K oxide—see p. 863). Three oxidative degradations reported by Doisy and his collaborators contributed a great deal to the elucidation of the structure of vitamin K_1. Mild chromic acid oxidation of vitamin K_1 yields 2-methyl-1,4-naphthoquinone-3-acetic acid, whereas the use of excess chromic acid yields phthalic acid. Ozonolysis of the diacetate of 2-methyl-3-phytyl-1,4-naphthohydroquinone (IV) yields 6,10,14-trimethyl-2-pentadecanone and 1,4-diacetoxy-2-methylnaphthalene-3-acetaldehyde. The reactions that have established the structure of vitamin K_1 have been reviewed in detail (1,21,27,72).

ISOLATION

The early work on the purification of vitamin K_1 was conducted by Almquist and by Dam. In 1939 Dam, Karrer, *et al.* reported the isolation of vitamin K_1 in what proved to be pure or approximately pure form. Doisy and co-workers independently isolated the pure vitamin in the same year. The vitamin or the dihydrovitamin diacetate can be extracted from alfalfa or other natural sources by petroleum ether or acetone. The pure vitamin can be obtained from the extracts by application of chromatographic adsorption and fractional distillation techniques and by selective crystallization of impurities (1,9,19,46,50,70). Almquist and Klose reported the isolation of vitamin K_1 as a choleic acid complex, from which the vitamin could be liberated (2). Fieser introduced a greatly simplified procedure (26) in which the vitamin is first converted into the dihydro derivative (IV). The latter, being less soluble in petroleum ether than the vitamin or substances that ordinarily accompany it in natural concentrates, can be made to separate from this solvent as a colorless, waxy solid. It is also possible to effect isolation of the dihydrovitamin, which is a weakly acidic compound,

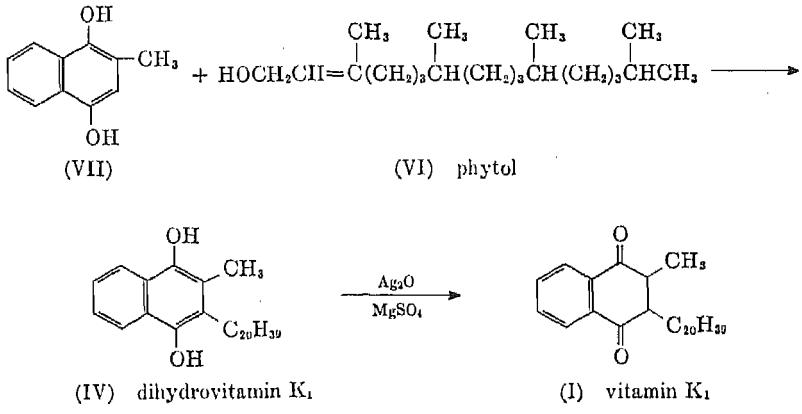
by extraction with Claisen's methanolic alkali solution; on diluting the alkaline extracts with water in the presence of ether, the dihydrovitamin passes into the ether phase. A preliminary announcement of reversed-phase partition chromatography on filter paper has appeared recently (42).

SYNTHESIS

Five independent syntheses of vitamin K_1 were reported in 1939, all making use of phytol, $C_{20}H_{39}OH$ (VI) (see Vol. **13,** p. 757), or its derivatives as phytylating agents for 2-methylnaphthoquinone or 2-methylnaphthohydroquinone. (*1*) Almquist and Klose (2): Phytyl bromide was refluxed with 2-methyl-1,4-naphthoquinone in petroleum ether in the presence of glacial acetic acid and zinc dust in the dark. The product was purified by fractional distillation and low-temperature crystallization. (*2*) Doisy and collaborators (55): Phytyl bromide was condensed with the monosodium salt of 2-methyl-1,4-naphthohydroquinone. After oxidation the vitamin was freed of impurities essentially by the procedure employed in the isolation of the natural material. (*3*) Isler (95): 2-Methyl-1,4-naphthohydroquinone was treated with the acetate of phytol in ether-benzene solution using zinc chloride as catalyst. The product, formulated as the 4-monoacetate of 2-methyl-3-phytyl-1,4-naphthohydroquinone, was purified by fractional distillation. (*4*) Lee (93): The alkylation of 2-methyl-1,4-naphthohydroquinone was carried out with phytyl bromide in acetone solution in the presence of potassium carbonate. Removal of unchanged starting material was followed by oxidation and further purification by chromatography and distillation. (*5*) Fieser (26): This method proved to be the most practical of the early syntheses of vitamin K_1.

The Fieser synthesis involves the condensation of phytol (VI) with 2-methyl-1,4-naphthohydroquinone (VII) in dioxane solution in the presence of acid, preferably oxalic acid, at 75°C. for 36 hours. Unchanged 2-methyl-1,4-naphthohydroquinone is removed by extraction with dilute alkali. The reaction product, dihydrovitamin K_1, which is insoluble in this reagent, is purified by precipitation from petroleum ether or extraction into Claisen's alkali and is then oxidized to vitamin K_1 in an overall yield of 29% (based on phytol). (See Scheme 1.) By-products include phytadiene, $CH_2{=}CHC(CH_3){=}CH(CH_2)_2CH(CH_3)(CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)_2$, and 2-

SCHEME 1



methyl-2-phytyl-2,3-dihydro-1,4-naphthoquinone (85). The latter compound has been converted into vitamin K_1 (85).

Other synthetic approaches to vitamin K_1 have been described, but the Fieser synthesis has remained the most useful for some fifteen years. More recently it has been shown that boron trifluoride etherate (44,47) and potassium acid sulfate (44) are far more efficient catalysts for the condensation reaction than the acids hitherto employed. It has also been shown that ethers and esters of phytol (44,47,95), as well as isophytol, $CH_2{=}CHC(CH_3)(OH)(CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)(CH_2)_3CH(CH_3)_2$, or its derivatives (47), can be employed as phytylating agents. (The boron trifluoride-catalyzed reaction has been employed for the preparation of C^{14}-labeled vitamin K_1 (43).) The most efficient synthesis reported to date (66% yield) is that of Hirschmann, Miller, and Wendler (44) in which the 1-monoacetate of 2-methyl-1,4-naphthohydroquinone (98) is allowed to react with phytol in the presence of potassium acid sulfate or boron trifluoride etherate (but not oxalic acid) as catalyst. The unchanged starting material can be removed by filtration after precipitation with petroleum ether. The condensation product, 2-methyl-3-phytyl-1,4-naphthohydroquinone 1-monoacetate, which—unlike (IV)—is soluble in petroleum ether, can be extracted into Claisen's alkali. This operation not only accomplishes separation of the dihydrovitamin from neutral impurities but also effects hydrolysis of the ester function at position 1.

ASSAY (29)

Volumetric Analysis. Vitamin K_1 and related quinones (E_0 = about 0.5 v.) can be quantitatively determined by catalytic (Raney nickel) hydrogenation of the vitamin in the presence of phenosafranine as indicator, followed by reoxidation with a standardized solution of 2,6-dichlorophenol-indophenol, which serves also as indicator for the titration (86).

Colorimetry. In a colorimetric modification of the above method the dihydrovitamin is treated with an excess of the indophenol; the decrease in color intensity due to the reduction of the dye by the hydroquinone is a measure of the amount of quinone originally present (80). The influence upon the test of certain extraneous reducing substances such as tocopherylhydroquinones has also been studied (81). Vitamin K_1 and menadione can also be determined by converting the quinones to derivatives formulated as phenylazonaphthols and measuring the color developed upon the addition of sulfuric or phosphoric acid (41). When a solution of sodium *N,N*-diethyldithiocarbamate and sodium ethoxide is added to vitamin K_1 or other 2,3-dialkylated 1,4-naphthoquinones, the deep blue color produced can be measured (45). The method has also been applied to menadione, which develops a pink color with the reagent.

Ultraviolet Spectroscopy. See p. 859.

Polarography. Vitamin K_1 in aqueous isopropyl alcohol containing potassium chloride shows a sharply defined wave at −0.58 v. (43).

Biological Methods (1,7,20,69,82,90). Various biological assay methods involving both curative and preventive procedures have been described. In general, two fundamental methods are commonly employed: (*1*) measurement of the clotting time of whole blood and (*2*) measurement of the "prothrombin time." The former method is less precise since the clotting power of whole blood depends on factors other than the prothrombin titer. Since the basic defect in vitamin K deficiency is a reduced prothrombin level (see p. 868), a better assay for vitamin K results if the prothrombin level is the sole variable in the assay. Several procedures have been designed to ap-

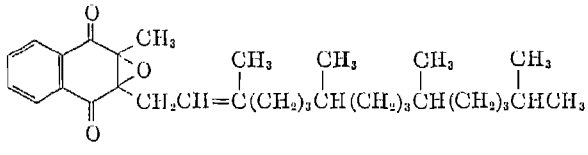
proximate this condition: (*a*) A one-stage method developed by Quick and modified by several investigators involves the addition to the plasma of thromboplastin and then of a calcium chloride solution. The time required, under carefully standardized conditions, for a firm clot to form is measured. (*b*) In the "two-stage" determination the fibrinogen is removed as fibrin by the addition of thrombin to the plasma. The remaining fluid contains the prothrombin, which is converted into thrombin with the aid of optimal amounts of calcium ions and an excess of a thromboplastic substance. The time required by the thrombin thus formed to cause clotting of a standardized fibrinogen solution is a measure of the amount of thrombin present. This thrombin level, in turn, is a function of the amount of prothrombin initially present.

Vitamin K_2

Vitamin K_2 (II) was isolated from putrefying fish meal by Doisy and his collaborators by means similar to those used for the isolation of vitamin K_1. The same compound was isolated by Tishler and Sampson from autolyzed cells of *Bacillus brevis*. Vitamin K_2 is a pale yellow crystalline solid, m.p. 53.5–54.5°C., $\lambda\lambda_{max.}$ 243 mμ (log ε 4.20), 249 mμ (4.24), 260 mμ (4.18), 270 mμ (4.18), and 325 mμ (3.45) (hexane) (25,62). It resembles vitamin K_1 in many of its physical and chemical properties, but vitamin K_2 is more unsaturated owing to the difarnesyl rather than the phytyl substituent in the 3-position (10). Vitamin K_2 gives an intense blue color in alcoholic sodium ethoxide solution. The chemistry of this commercially unimportant vitamin has been summarized (1,21).

Vitamin K_1 Oxide

Vitamin K_1 oxide (VIII), $C_{31}H_{46}O_3$, is a nearly colorless oil, $\lambda\lambda_{max.}$ 259 mμ (log ε 3.79), 305 mμ (3.31) (95% alcohol) (85). The oxide does not respond to the Dam-Karrer test, but on warming with alcoholic alkali it gives a red coloration. It has the advantage over the natural vitamins of being much more stable to light and heat while still possessing antihemorrhagic activity of the same high order.



(VIII) Vitamin K_1 oxide

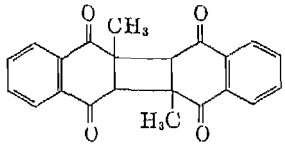
The oxide has been prepared from vitamin K_1 (35) by treatment with hydrogen peroxide and aqueous sodium carbonate at 75°C. in 82% yield. Shaking a methanolic solution of the oxide with hydrosulfite effects smooth conversion to dihydrovitamin K_1 even at room temperature.

2-Methyl-1,4-naphthoquinone (Menadione)

Of many simple modifications of the vitamin K_1 molecule tested for biological activity only 2-methyl-1,4-naphthoquinone proved more active than the natural vitamin on a weight basis by the chick assay test (4) (see p. 868).

PHYSICAL AND CHEMICAL PROPERTIES

2-Methyl-1,4-naphthoquinone (menadione, U.S.P. XV, N.N.R., menaphthone, vitamin K_3) (III), $C_{11}H_8O_2$, is a crystalline solid, m.p. 105–106°C. It is soluble in benzene and in ether, somewhat less soluble in glacial acetic acid, and only sparingly soluble in ligroin. The solubility in 95% alcohol is reported to be 17 mg./ml. and in sesame oil 13 mg./ml. While the compound is only slightly soluble in water, it dissolves readily in an aqueous solution of sodium dehydrocholate. Menadione is sensitive to heat. The action of light produces a colorless compound formulated as the dimer (IX). The oxidation potential, E_0, of menadione in 70% alcohol, 0.2 *N* in hydrochloric acid and 0.2 *N* in lithium chloride, is 0.408 v. (25°C.) (32). In 50% alcohol, 0.1 *N* in hydrochloric acid and 0.2 *N* in lithium chloride, E_0 is 0.422 v. (25°C.) (53,89). In a polarographic reduction in 75% alcoholic acetate buffer (pH 6.24) menadione gives a step at −0.17 v. (66,77). In the ultraviolet spectrum vitamin K_3 exhibits maxima at 244 mμ (log ε 4.30), 253 mμ (4.29–4.31), 263–264 mμ (4.22), and 334 mμ (3.4–3.5) (hexane (25) or isooctane (5)). A value of 4.30 for log ε at 263 mμ has been reported (62). In alcoholic solution or in alcohol containing chloroform (44) the maxima are at 245 mμ (log ε 4.26), 250 mμ (4.28), 262 mμ, (4.18), and 330 mμ (3.4) (5). The infrared spectrum of menadione has been reported by Rosenkrantz (73).

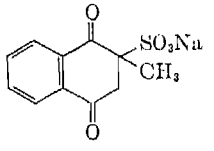


(IX)

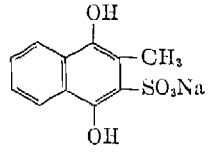
Menadione resembles vitamin K_1 in some of its chemical properties. On warming with a 0.5% solution of sodium hydroxide in contact with air on a waterbath or by treatment with alcoholic alkali it is converted into phthiocol. Menadione can be oxidized with dilute nitric acid to phthalic acid. Reduction of the quinone to the naphthohydroquinone can be effected by the same methods as for vitamin K_1 and by additional procedures that would reduce the phytyl double bond in vitamin K_1 or cyclize the dihydrovitamin (IV→V). Thus menadione can be subjected to catalytic hydrogenation with platinum (until one mole of hydrogen has been taken up) or with a palladium catalyst (in ethereal or methanolic solution) or to reduction in acid solution by a variety of methods. The resulting *2-methyl-1,4-naphthohydroquinone* (menadiol) is readily soluble in dilute aqueous alkali solution which should contain sodium hydrosulfite as an antioxidant. The free phenol can be recovered from the alkaline liquor by acidification with acetic acid followed by ether extraction. A number of diesters including 2-methyl-1,4-naphthohydroquinone diacetate (acetomenaphthone, B.P.C., vitamin K_4) have been prepared from menadione by reductive acylation procedures. Complete hydrogenation of menadione in acetic acid in the presence of a platinum catalyst yields 2-methyl-5,6,7,8-tetrahydro-1,4-naphthohydroquinone.

It is well known that simple quinones such as naphthoquinone undergo 1,4-addition reactions with reagents of the type HX (see Vol. **11**, p. 416). The 2-methyl group of menadione exerts a distinct retarding effect on the introduction of substituents at the 3-position by way of 1,4-addition reactions (56). Menadione in its reactivity toward HX reactants is, therefore, intermediate between naphthoquinone and

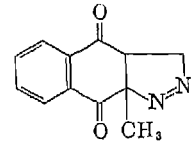
vitamin K_1. Methylamine, for example, reacts with menadione to give 2-methyl-3-methylamino-1,4-naphthoquinone but no 1,4-addition reaction occurs with aniline (38). The red color developed from treatment of menadione with aniline (29) is, however, the basis of an analytical method (58) for the determination of menadione. An analogous 1,4-addition occurs with azide in aqueous alcohol (39) but not in dilute acetic acid (34). Sulfhydryl (mercapto) compounds add rapidly to methylnaphthoquinone. Another example of 1,4-addition is the preparation of 2-methyl-3-bromonaphthoquinone from methylnaphthoquinone on treatment with acetic acid saturated with hydrogen bromide, followed by the action of nitric acid. Menadione reacts (61) readily in aqueous solution with sodium bisulfite and other bisulfite salts to form two series of isomeric addition compounds: salts of 2-methyl-2,3-dihydro-1,4-napthoquinone-2-sulfonic acid (X), having high antihemorrhagic activity (13), and salts of 2-methyl-1,4-naphthohydroquinone-3-sulfonic acid (XI), having only little activity (6). Grignard reagents react with menadione to give products of 1,4- and 1,2-addition (17).



(X)



(XI)



(XII)

Menadione can react also by direct addition to the quinonoid ethylenic linkage which is not shared with the aromatic ring. This type of addition is exemplified by Diels-Alder reactions with conjugated dienes and by the formation of the 2,3-epoxide or of the corresponding dihalides. The dibromide on dehydrohalogenation gives 2-methyl-3-bromo-1,4-naphthoquinone. Addition reactions occur also with unsaturated nitrogen compounds. Thus diazomethane yields (XII) in addition to 2,3-dimethyl-1,4-naphthoquinone and bis(3-methyl-1,4-naphthoquinon-2-yl)methane.

Typical reactions of menadione with carbonyl reagents are referred to under "Assay." For a discussion of quinone substitution reactions, see Vol. **11**, p. 415.

SYNTHESIS

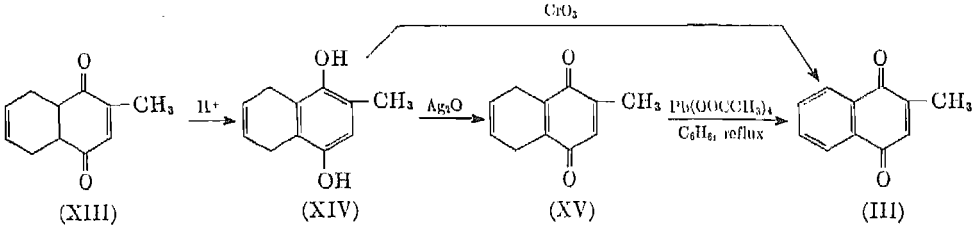
In 1924 Vesely and Kapps described a simple procedure for the preparation of 2-methyl-1,4-naphthoquinone from 2-methylnaphthalene by chromic anhydride oxidation in acetic acid solution (88). Several modifications of this important method have been employed. The highest yields reported are 25–40% (84), 37–39% (96), 38–42% (28), 45% (87), and 50–60% (92). Sah (76) synthesized menadione from pentosans and from hexosans via 2-methylnaphthalene by a series of transformations that can be utilized to incorporate C^{14} into the benzenoid ring. Other reagents for oxidizing the methylnaphthalene to menadione include hydrogen peroxide in acetic acid (30% yield), chromic oxide, and sodium dichromate – sulfuric acid (35% yield) (see also ref. 103).

Menadione has also been prepared from derivatives of 2-methylnaphthalene containing hydroxy, alkoxy, or amino groups in positions 1 and/or 4. Thus 2-methyl-1,4-naphthohydroquinone is oxidized to the quinone by reagents such as chromic anhydride in acetic acid, ferric chloride or nitric acid in acetic acid, or by heating with *p*-nitrosodimethylaniline in boiling alcohol. (The last-named oxidizing agent may also be employed to convert 2-methyl-2,3-dihydro-1,4-naphthoquinone to menadione.) Mena-

dione has further been prepared by adding an excess of hydrogen peroxide to 2-methyl-1-aminonaphthalene sulfate in boiling acetic acid (38) (81% yield); by treating 2-methyl-1,4-diaminonaphthalene hydrochloride in acetic acid solution with ferric chloride (88); by oxidizing 2-methyl-4-chloro-1-naphthol in acetic acid solution with ferric chloride (nearly quantitative yield) or—less smoothly—with hydrogen peroxide or nitric acid (38). Other routes to menadione include the oxidation of 2-methyl-4-amino-1-naphthol and its 3-methyl isomer; of 3-methyl-1-naphthol; and of the 1,4-dimethyl ether of 2-methyl-1,4-naphthohydroquinone. The conversion of 2-alkyl-3-carbethoxy-1,4-naphthohydroquinones to the corresponding 2-alkyl-1,4-naphthoquinones has been described.

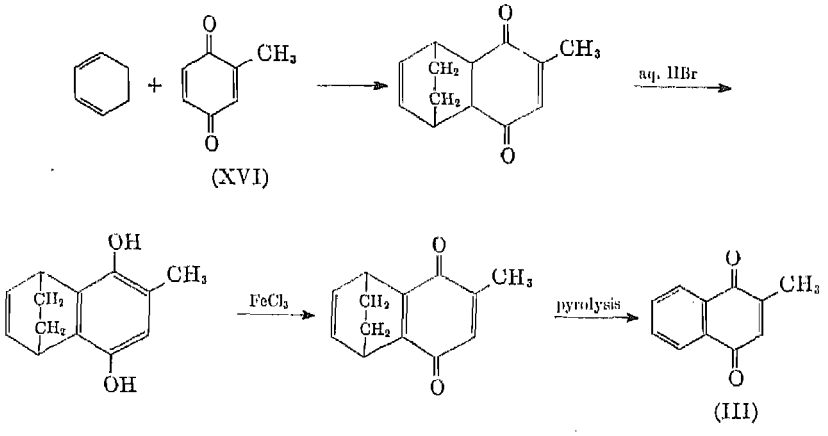
Another synthesis of menadione involves the Diels-Alder condensation of butadiene with *p*-toluquinone (XVI) (30,31,37,85) to give (XIII), which is isomerized to the 5,8-dihydronaphthalene derivative (XIV) in good overall yield. Alternatively, (XIV) can be obtained directly when the condensation is carried out in nitrobenzene or in acetic acid solution. Oxidation of (XIV) with chromic anhydride gives a 58% yield of menadione, or with silver oxide followed by lead tetraacetate a moderate yield. (See Scheme 2.)

SCHEME 2



A different Diels-Alder synthesis from *p*-toluquinone (XVI) gives a 75% overall yield of menadione (40) (see Scheme 3). Diels-Alder reactions are also involved in the conversion of 5-methyl-2-acetoxy-*p*-benzoquinone to menadione (see Vol. **11**, p. 415).

SCHEME 3



Finally, menadione can be prepared from its 4-oxime by a variety of methods. The oxime is available in good yield from the condensation of 2-methyl-1-naphthol with isoamyl nitrite.

ASSAY

Volumetric Analysis. Menadione can be titrated with titanous chloride using potassium indigodisulfonate as indicator (67). It can be determined by reduction to the hydroquinone followed by titration of the latter with ceric sulfate in the presence of 4′-ethoxychrysoidine (79). In a similar procedure *o*-phenanthroline serves as indicator (74). Menadione can also be reduced with potassium iodide in alcoholic solution in the presence of hydrochloric acid and the liberated iodine titrated (91). Another procedure involves treatment of menadione with an excess of bromine and back-titration of the unchanged bromine (74).

Colorimetry. In 1941 Novelli (64) reported a method that involves treating the quinone with 2,4-dinitrophenylhydrazine and measuring the green color that develops when the derivative is treated with ammonia. Several modifications of Novelli's method have been described. Another procedure for quinones having "a labile hydrogen or halogen atom adjacent to the carbonyl group" is based on the intense bluish-violet color that develops after the addition of 2–3 drops of ethyl cyanoacetate and alcoholic ammonia water (16,51,67). Treatment of a methanolic solution of menadione with sodium hydroxide and dichlorophenol-indophenol produces a green color that can be extracted with amyl alcohol and determined colorimetrically (11). A less sensitive method than these involves measurement of the color developed on treatment of menadione with sodium alkoxide (11,14). In one modification menadione or methylnaphthohydroquinone diacetate is used in oil solution (15) and in another the diacetate in methylacetamide gives a red color on addition of sodium hydroxide (3). The time from the addition of the alkali to the appearance of a red color is an inverse function of the concentration of the diacetate present (3). A rapid colorimetric determination of menadione in alcoholic, aqueous, or ether-alcoholic solution or in plasma or urine consists in the development of a yellow color when cysteine and sodium hydroxide are added to a solution of menadione (80). The red color reaction with aniline is also useful (see p. 865).

Ultraviolet Spectroscopy. See p. 864.

Fluorometry. According to Kofler (51) menadione forms a fluorescent compound by condensation with *o*-phenylenediamine. The blue fluorescence of an alcoholic solution of this compound is so intense that it can be detected in very dilute solutions.

Gravimetric Analysis. The precipitate obtained with 2,4-dinitrophenylhydrazine can be determined.

TABLE I. Total Production and Sales of Vitamin K.

Year	Production, lb.	Sales		
		Quantity, lb.[a]	Value, $	Unit value /lb., $
1941–43	—	—	7,000	53.89
1944	400	200	23,500	117.50
1945	900	700	73,400	104.86
1946	400	200	50,900	254.50
1947	1100	1200	87,400	72.83
1948	—	—	—	—
1949	800	60	17,000	289.83
1950	—	—	—	—
1951	1900	650	25,000	38.22
1952	1000	390	19,000	49.31
1953	1000	1000	21,000	28.13

[a] Recalculated in pounds by dividing value for total sales by unit value.

Economic Aspects

The production and sales of all types of vitamin K, as given by the U.S. Tariff Commission, are presented in Table I.

Biological Action and Uses

Vitamin K is required for the synthesis of prothrombin in the liver. (See refs. 65 and 68 for a discussion of the vitamin K requirements in animals and in man.) For the purpose of this discussion the role of the prothrombin in the blood-clotting mechanism may be presented thus (see also ref. 57):

$$\text{prothrombin} \xrightarrow{Ca^{2+} + \text{thromboplastin}} \text{thrombin}$$

$$\text{fibrinogen} \xrightarrow{\text{thrombin}} \text{fibrin}$$

A deficiency of vitamin K in the diet or interference with its absorption causes a lowered prothrombin content in the blood (hypoprothrombinemia), which in turn gives rise to the hemorrhagic syndrome. Inadequate absorption of the vitamin may be due to the absence of bile in the intestine as, for example, in cases of obstructive jaundice and biliary fistula. In all instances involving a lack of bile secretion into the intestine, the use of compounds with vitamin K activity is advisable. Surgery in such cases would present great hazards unless the hemorrhagic tendency had been diminished by the prior administration of vitamin K. Compounds with vitamin K activity may be administered parenterally in aqueous medium (see p. 870) or orally using bile salts if necessary. In combination with vitamin C (ascorbic acid), vitamin K is recommended for preventing post-operative hemorrhage, as after tonsillectomy, and for promoting healing of wounds.

Another important use has been the prevention of hemorrhage in the newborn infant. The intestinal tract of the newborn is sterile so that the bacterial synthesis of the vitamin normally occurring there does not take place. The administration of vitamin K to the mother during labor or to the infant after delivery prevents hemorrhages in the child.

Vitamin K therapy can also raise the prothrombin level which has been lowered as a result of the use of certain drugs such as sulfonamides and salicylates, and of anticoagulants such as 2-phenyl-1,3-indandione (phenindione, N.N.R.), Cumopyran (cyclocumarol, N.N.R., 3,4-dihydro-2-methoxy-2-methyl-4-phenyl-2*H*,5*H*-pyrano[3,2-*c*][1]benzopyran-5-one), or those of the type of Dicoumarol (bishydroxycoumarin, U.S.P. XIV, N.N.R., 3,3′-methylenebis(4-hydroxycoumarin)—see Vol. **4**, p. 593). Since there is no satisfactory method for predicting the requisite dosage of anticoagulants, a dangerously low prothrombin activity may result. Vitamin K_1 may be effectively and safely given to counteract the excesses of anticoagulant therapy.

Chemical Structure and Vitamin K_1 Activity. *Effectiveness against Hypoprothrombinemia Caused, for example, by Dietary Deficiency and Inadequate Absorption from the Intestinal Tract.* Many simple modifications of the vitamin K_1 molecule have shown antihemorrhagic activity in chicks but, except for menadione, the activity of these compounds has been of a lower order than that of the natural vitamins and of vitamin K_1 oxide. Bioassays were reported by Fieser, Tishler, and Sampson (36) for 79 compounds on a weight basis and summarized in part by Fieser (29) in a chart (Fig. 1). Menadione possesses about three times the activity of vitamin K_1 when

measured on a weight basis (4,36) but approximately the same activity on a molecular basis. However, in rate tests with vitamin K-deficient chicks, vitamin K_1 raises the prothrombin level considerably faster, particularly during the first hour after administration of the drug, than menadione or the tetrasodium salt of the diphosphate administered in equimolar dosages (15).

Effectiveness against Hypoprothrombinemia Caused by Anticoagulants and Certain Other Drugs. Vitamin K_1 and its oxide, but not menadione and its water-soluble derivatives, proved effective in the treatment of hypoprothrombinemia induced in dogs and rats by 2-sulfanilamidoquinoxaline (sulfaquinoxaline) (63). Similarly vitamin K_1 but not menadione and its water-soluble forms could be relied on to overcome

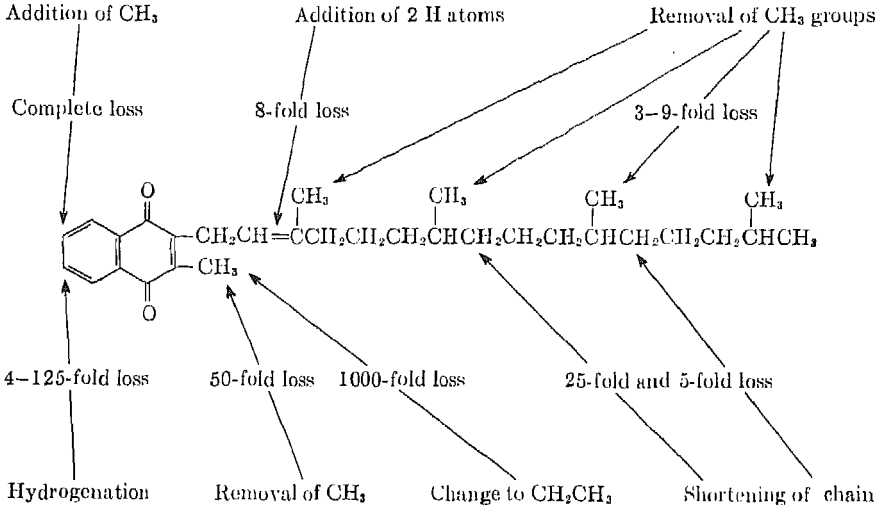


Fig. 1. Specificity of the vitamin K_1 structure. Loss in activity attending alterations in the vitamin K_1 molecule (29).

the effects of excessive anticoagulant therapy in man (18,22,49,60,83). Isler, Rüegg, Studer, and Jürgens (48) studied the effects of changes in the substituent at C(3) upon the efficacy of the resulting compound in overcoming hypoprothrombinemia induced in rats and rabbits with Dicoumarol and other anticoagulants related to 4-hydroxycoumarin. The compounds studied included (*1*) lower and higher homologs of vitamin K_1, (*2*) lower isoprenologs of vitamin K_2, and (*3*) compounds having other aliphatic side chains at C(3), including those with alicyclic or aromatic substituents. A general conclusion was that for a given compound the activity might vary with the species of the test animal or with the nature of the anticoagulant. Vitamin K_1 itself, however, was found to be fully effective in both species and against all the anticoagulants studied. On the other hand, menadione and compounds having a 3-substituent with fewer than eight carbons were inactive. The presence of a double bond in the β,γ-position and branching in the side chain were found to contribute to potency, but they were not required for activity.

Toxicity. Neither hypercoagulability nor any other toxic effect of the blood results from the administration of even large doses of vitamin K_1. From studies on animals it seems likely that man can tolerate amounts of the K vitamins larger than those now administered (65). Vitamin K_1 can be given safely at considerably higher

dosages than menadione and its derivatives. When menadione is given orally to rats daily for thirty days, the lethal dose is 500 mg./kg. body weight, whereas vitamin K_1 is not toxic at a level of 25 g./kg. of body weight. It has also been reported that on lengthening the solubilizing ester chains of menadione, the toxicity decreases much more rapidly than the antihemorrhagic activity.

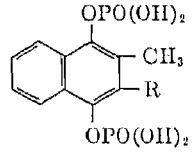
Menadione powder is irritating to the respiratory tract and to the skin, and an alcoholic solution has vesicant properties.

Preparations Suitable for Intravenous Administration

The natural K vitamins as well as menadione are fat-soluble substances, and it is therefore often desirable for proper absorption from the intestinal tract, to administer bile salts simultaneously. When particularly rapid action is desired or when oral administration is contraindicated, preparations suitable for parenteral use become important. To make possible the intravenous administration of vitamin K_1 and of menadione, early workers diluted alcoholic solutions with saline or glucose solutions. This practice is no longer necessary since a stable emulsion of vitamin K_1 can now be prepared. In addition, potent compounds related to menadione that are soluble in aqueous medium are now commercially available. The water-soluble compounds have the additional advantage that they can be given orally without bile salts. The examples listed below serve only to illustrate the types of preparations in aqueous medium which have been described in the literature. In general, the antihemorrhagic activity observed with the water-soluble compounds discussed below does not seem to be attributable to the functioning of the substances administered per se but rather to their conversion in the animal body to the vitamin K principle from which they are derived (36). Consequently only aqueous preparations of compounds that are related to vitamin K_1 should be expected to be effective against anticoagulant-induced hypoprothrombinemia.

PREPARATIONS RELATED TO VITAMIN K_1

The synthesis of the water-soluble **diphosphate ester** (XVII) by treating the dihydrovitamin (IV) with phosphorus oxychloride in pyridine solution has been described by Fieser and co-workers (33,36,104).



(XVII) R = phytyl
(XVIII) R = H

An **emulsion** of vitamin K_1 suitable for intravenous administration became commercially available in 1952.

PREPARATIONS RELATED TO MENADIONE

Solutions. Menadione is reported to be "readily soluble" in a 5% aqueous solution of sodium dehydrocholate (12). Furthermore, 5.0 g. of menadione dissolves readily in 500 ml. of a 50% solution of sodium salicylate in water (94).

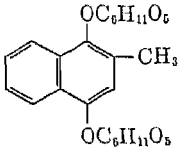
Water-Soluble Derivatives. A number of derivatives of menadione have been reported (102) that are water-soluble by virtue of their ability to form salts with alkali. The sodium salt of 2-methyl-1,4-naphthohydroquinone itself is extremely sensitive to air oxidation and is therefore unsuitable. A more stable derivative is obtained, however, by reductive acylation of menadione with the anhydride of a dibasic acid such as succinic anhydride. Upon the addition of the theoretical amount of alkali a water-soluble sodium salt is obtained.

Of considerable commercial importance are the solutions of **"menadione sodium bisulfite"** U.S.P. XV, N.N.R. (97,100) (see p. 865). The 2,3-dihydro quinone-2-sulfonic acid structure (X), satisfactorily explains the ultraviolet spectrum (44), the stability in neutral or acidic media and resistance to oxidation, the ready regeneration of 2-methylnaphthoquinone in alkaline medium, the equivalence in physiological activity of the salt and menadione, and the isomerization to the weakly active salt (XI) upon prolonged heating (13). Methods for analytical determinations of menadione sodium bisulfite have been described (59,78).

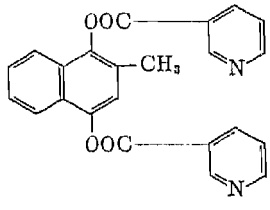
Phosphoric acid **esters** (XVIII) (33,104) of 2-methylnaphthohydroquinone constitute another commercially important class of water-soluble forms of menadione. The bis(dichlorophosphoryl) ester is readily prepared from the hydroquinone and phosphorus oxychloride in the presence of pyridine. The tetrachloride is hydrolyzed and the resulting ester (XVIII) is converted into salts, such as *sodium menadiol diphosphate*, U.S.P. XV, N.N.R., $C_{10}H_5(CH_3)(O_4PNa_2)_2 \cdot 6H_2O$, a white or pink to light brown hygroscopic powder.

The sodium salts of the disulfate esters of methylnaphthohydroquinone (33) can be prepared from chlorosulfonic acid and the hydroquinone. The preparation of the 4-disodium phosphate and the 4-sodium sulfate esters of 2-methyl-1,4-naphthohydroquinone 1-acetate from the 1-monoacetate of methylnaphthohydroquinone (98) can be carried out by the above reactions.

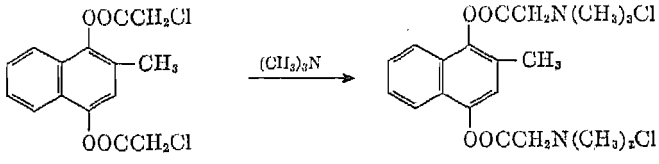
Water solubility may also be achieved by preparing **glycosides** of the hydroquinone (98a,99). For example, condensation of β-D-glucose pentaacetate with 2-methyl-1,4-naphthohydroquinone in the presence of *p*-toluenesulfonic acid at about 130°C. affords the bis(glucoside tetraacetate). The latter is purified and subsequently hydrolyzed to give the deacetylated, water-soluble product (XIX). When the 1-



(XIX)



(XX)



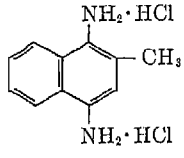
(XXI) (XXII)

monoacetate of methylnaphthohydroquinone is employed as the starting material, the product, after hydrolysis, is the 4-monoglucoside.

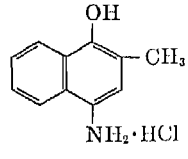
The syntheses of a number of basic **nitrogen derivatives** of 2-methyl-1,4-naphthohydroquinone that form water-soluble salts such as hydrochlorides have been described (105). Thus acylation of the methylhydroquinone with nicotinyl chloride in pyridine solution gives the dinicotinate (XX), the hydrochloride of which is water-soluble.

Another type of nitrogen-containing-derivative owes its water solubility to quaternary salt formation (101). Thus from the treatment of a solution of the diester (XXI) with trimethylamine, the water-soluble salt (XXII) is obtained.

Other types of water-soluble preparations are substitution products of 2-methyl-1,4-naphthohydroquinone containing nitrogen attached directly to the aromatic nucleus, for example, **2-methyl-4-amino-1-naphthol hydrochloride** (XXIV) (vitamin K_5) (23). The preparation of this compound from menadione has been described by a number of workers (75,87). Treatment of menadione with hydroxylamine hydrochloride affords the 4-monoxime, which can be reduced to the desired compound with stannous chloride in concentrated hydrochloric acid or by catalytic hydrogenation. Other carbonyl derivatives of menadione serve as intermediates in the synthesis (see Vol. **11**, p. 413). Aqueous solutions of 2-methyl-4-amino-1-naphthol hydrochloride are sensitive to air oxidation and must be stabilized by the addition of reducing agents such as potassium metabisulfite. A colorimetric determination (59) based on the reaction between 2-methyl-4-amino-1-naphthol and sodium pentacyanoammineferrate (II) has been described. No color is obtained with menadione under the conditions employed.



(XXIII)



(XXIV)

The synthesis of **2-methyl-1,4-diaminonaphthalene dihydrochloride** (vitamin K_6) (XXIII) has been described (87,88). This compound is reported to be more stable and more soluble in aqueous solutions than vitamin K_5.

Bibliography

(1) Almquist, H. J., *Physiol. Revs.*, **21**, 194 (1941).
(2) Almquist, H. J., and Klose, A. A., *J. Am. Chem. Soc.*, **61**, 745, 2557 (1939).
(3) Anderson, R. J., and Newman, M. S., *J. Biol. Chem.*, **103**, 405 (1933).
(4) Ansbacher, S., and Fernholz, E., *J. Am. Chem. Soc.*, **61**, 1924 (1939).
(5) Bacher, F. A., and Hirschmann, R., unpublished observation.
(6) Baker, B. R., Davies, T. H., McElroy, L., and Carlson, G. H., *J. Am. Chem. Soc.*, **64**, 1096 (1942).
(7) Bicknell, F., and Prescott, F., *The Vitamins in Medicine*, Grune & Stratton, N.Y., 1953, pp. 686–730.
(8) Binkley, S. B., MacCorquodale, D. W., Cheney, L. C., Thayer, S. A., McKee, R. W., and Doisy, E. A., *J. Am. Chem. Soc.*, **61**, 1612 (1939).
(9) Binkley, S. B., MacCorquodale, D. W., Thayer, S. A., and Doisy, E. A., *J. Biol. Chem.*, **130**, 219 (1939).
(10) Binkley, S. B., McKee, R. W., Thayer, S. A., and Doisy, E. A., *J. Biol. Chem.*, **133**, 721 (1940).
(11) Bosecke, W., and Laves, W., *Biochem. Z.*, **314**, 285 (1943).
(12) Cantarow, A., Paschkis, K. E., Rakoff, A. E., and Hansen, L. P., *Endocrinology*, **35**, 129 (1944).
(13) Carmack, M., Moore, M. B., and Balis, M. E., *J. Am. Chem. Soc.*, **72**, 844 (1950).
(14) Carrara, G., Braidotti, L., and Guidarini, C., *Chimica e industria Milan*, **22**, 317 (1940); *C.A.*, **35**, 1836.

(15) Colluci, D. B., *Ann. chim. appl.*, **36**, 97 (1946); *C.A.*, **40**, 6527.
(16) Craven, R., *J. Chem. Soc.*, **1931**, 1605.
(17) Crawford, H. M., *J. Am. Chem. Soc.*, **63**, 1070 (1941).
(18) Dam, H., *Proc. Nutrition Soc.*, **12**, 114 (1953).
(19) Dam, H., Geiger, A., Glavind, J., Karrer, P., Karrer, W., Rothschild, E., and Salomon, H., *Helv. Chim. Acta*, **22**, 310 (1939).
(20) Dam, H., Kruse, I., and Søndergaard, E., *Acta Physiol. Scand.*, **22**, 238 (1951).
(21) Doisy, E. A., Binkley, S. B., and Thayer, S. A., *Chem. Revs.*, **28**, 477 (1941).
(22) Douglas, A. S., and Brown, A., *Brit. Med. J.*, **1952, I**, 412.
(23) Emmett, A. D., Kamm, O., and Sharp, E. A., *J. Biol. Chem.*, **133**, 285 (1940).
(24) Ewing, D. T., Tomkins, F. S., and Kamm, O., *J. Biol. Chem.*, **147**, 233 (1943).
(25) Ewing, D. T., Vandenbelt, J. M., and Kamm, O., *J. Biol. Chem.*, **131**, 345 (1939).
(26) Fieser, L. F., *J. Am. Chem. Soc.*, **61**, 2559, 3467 (1939).
(27) Fieser, L. F., *Science*, **91**, 31 (1940).
(28) Fieser, L. F., *J. Biol. Chem.*, **133**, 391 (1940).
(29) Fieser, L. F., *Ann. Internal Med.*, **15**, 648 (1941).
(30) Fieser, L. F., and Chang, F. C., *J. Am. Chem. Soc.*, **64**, 2043 (1942).
(31) Fieser, L. F., and Oxford, A. E., *J. Am. Chem. Soc.*, **64**, 2060 (1942).
(32) Fieser, L. F., and Fieser, M., *J. Am. Chem. Soc.*, **57**, 491 (1935).
(33) Fieser, L. F., and Fry, E. M., *J. Am. Chem. Soc.*, **62**, 228 (1940).
(34) Fieser, L. F., and Hartwell, J. L., *J. Am. Chem. Soc.*, **57**, 1482 (1935).
(35) Fieser, L. F., Tishler, M., and Sampson, W. L., *J. Am. Chem. Soc.*, **62**, 1628 (1940).
(36) Fieser, L. F., Tishler, M., and Sampson, W. L., *J. Biol. Chem.*, **137**, 659 (1941).
(37) Fieser, L. F., Tishler, M., and Wendler, N. L., *J. Am. Chem. Soc.*, **62**, 2861 (1940).
(38) Fries, K., and Lohmann, W., *Ber.*, **54**, 2912 (1921).
(39) Fries, K., and Ochwat, P., *Ber.*, **56**, 1291 (1923).
(40) Grdinić, M. R., and Jugovic, V. K., *Arhiv. Kem.*, **23**, 73 (1951); *C.A.*, **46**, 11165.
(41) Greco, D., and Argenziano, R., *Boll. soc. ital. biol. sper.*, **19**, 171 (1944); *C.A.*, **40**, 7516.
(42) Green, J. P., *Nature*, **174**, 369 (1954).
(43) Hershberg, E. B., Wolfe, J. K., and Fieser, L. F., *J. Am. Chem. Soc.*, **62**, 3516 (1940).
(44) Hirschmann, R., Miller, R., and Wendler, N. L., *J. Am. Chem. Soc.*, **76**, 4592 (1954).
(45) Irreverre, F., and Sullivan, M. X., *Science*, **94**, 497 (1941).
(46) Isler, O., *Chimia (Switz.)*, **5**, 249 (1951).
(47) Isler, O., and Doebel, K., *Helv. Chim. Acta*, **37**, 225 (1954).
(48) Isler, O., Rüegg, R., Studer, A., and Jürgens, R., *Z. physiol. Chem.*, **295**, 290 (1953).
(49) James, D. F., Bennett, I. L., Jr., Scheinberg, P., and Butler, J. J., *Arch. Internal Med.*, **83**, 632 (1949).
(50) Karrer, P., and Geiger, A., *Helv. Chim. Acta*, **22**, 945 (1939).
(51) Kofler, M., *Helv. Chim. Acta*, **28**, 702 (1945).
(52) Lindlar, H., *Helv. Chim. Acta*, **35**, 446 (1952).
(53) Lugg, J. W. H., Macbeth, A. K., and Winzor, F. L., *J. Chem. Soc.*, **1936**, 1457.
(54) MacCorquodale, D. W., Binkley, S. B., Thayer, S. A., and Doisy, E. A., *J. Am. Chem. Soc.*, **61**, 1928 (1939).
(55) MacCorquodale, D. W., Cheney, L. C., Binkley, S. B., Holcomb, W. F., McKee, R. W., Thayer, S. A., and Doisy, E. A., *J. Biol. Chem.*, **131**, 357 (1939).
(56) Madinaveitia, J., *Anales soc. españ. fis. y quim.*, **31**, 750 (1933).
(57) Marbet, R., and Winterstein, A., *Experientia*, **10**, 273 (1954).
(58) Martinson, E. E., and Meerovich, G. I., *Biokhimiya*, **10**, 258 (1945); *C.A.*, **39**, 5274.
(59) Menotti, A. R., *Ind. Eng. Chem., Anal. Ed.*, **14**, 418, 601 (1942); *J. Am. Chem. Soc.*, **65**, 1209 (1943).
(60) Miller, R., Harvey, W. P., and Finch, C. A., *New England J. Med.*, **242**, 211 (1950).
(61) Moore, M. B., *J. Am. Chem. Soc.*, **63**, 2049 (1941).
(62) Morton, R. A., and Earlam, W. T., *J. Chem. Soc.*, **1941**, 159.
(63) Mushett, C. W., and Seeler, A. O., *J. Pharmacol. Exptl. Therap.*, **91**, 84 (1947).
(64) Novelli, A., *Science*, **93**, 358 (1941).
(65) Owens, C. A., Jr., Harris, R. S., and Almquist, H. J., in Sebrell and Harris, *The Vitamins*, Academic Press, N.Y., 1954, Vol. II, pp. 387–448.
(66) Page, J. E., and Robinson, F. A., *J. Chem. Soc.*, **1943**, 133.
(67) Pinder, J. L., and Singer, J. H., *Analyst*, **65**, 7 (1940).
(68) Quick, A. J., Hussey, C. A., and Collentine, G. E. Jr., *Am. J. Physiol.*, **176**, 239 (1954).
(69) Quick, A. J., Stanley-Brown, M., and Bancroft, F. W., *Am. J. Med. Sci.*, **190**, 501, (1935).
(70) Riegel, B., Schweitzer, C. E., and Smith, P. G., *J. Biol. Chem.*, **129**, 495 (1939).

(71) Riegel, B., Smith, P. G., and Schweitzer, C. A., *J. Am. Chem. Soc.*, **62**, 992 (1940).
(72) Rosenberg, H. R., *Chemistry and Physiology of the Vitamins*, rev. reprint, Interscience, N.Y.-London, 1945, pp. 481-509.
(73) Rosenkrantz, H., *J. Biol. Chem.*, **173**, 439 (1948).
(74) Rosin, J., Rosenblum, H., and Mack, R., *Am. J. Pharm.*, **113**, 434 (1941).
(75) Sah, P. P. T., *Rec. trav. chim.*, **59**, 454, 1029 (1940); **60**, 373 (1941).
(76) Sah, P. P. T., *Z. Vitamin-, Hormon- u. Fermentforsch.*, **3**, 40 (1949); *C.A.*, **44**, 5857.
(77) Sartori, G., and Cattaneo, C., *Gazz. chim. ital.*, **71**, 713 (1941); *C.A.*, **36**, 7018.
(78) Schoen, K., *J. Am. Pharm. Assoc.*, **34**, 247 (1945).
(79) Schulek, E., and Rozsa, P., *Mikrochemie ver. Mikrochim. Acta*, **29**, 178 (1941).
(80) Scudi, J. V., and Buhs, R. P., *J. Biol. Chem.*, **141**, 451 (1941).
(81) Scudi, J. V., and Buhs, R. P., *J. Biol. Chem.*, **143**, 665 (1942).
(82) Seegers, W. H., *Pharmacol. Revs.*, **3**, 278 (1951).
(83) Smith, C. C., Fradkin, R., and Lackey, M. D., *Proc. Soc. Exptl. Biol. Med.*, **61**, 398 (1946).
(84) Smith, L. I., and Webster, J. M., *J. Am. Chem. Soc.*, **59**, 662 (1937).
(85) Tishler, M., Fieser, L. F., and Wendler, N. L., *J. Am. Chem. Soc.*, **62**, 1982, 2866 (1940).
(86) Trenner, N. R., and Bacher, F. A., *J. Biol. Chem.*, **137**, 745 (1941).
(87) Veldstra, H., and Wiardi, P. W., *Rec. trav. chim.*, **62**, 75 (1943).
(88) Vesely, V., and Kapp, J., *Chem. Listy*, **18**, 201 (1924); *Rec. trav. chim.*, **44**, 360 (1925).
(89) Wallenfels, K., and Möhle, W., *Ber.*, **B76**, 924 (1943).
(90) Warner, E. D., Brinkhous, K. M., and Smith, H. P., *Am. J. Physiol.*, **114**, 667 (1936).
(91) Zakharova, M. P., and Devyatnin, V. A., *Biokhimiya*, **9**, 256 (1944); *C.A.*, **39**, 3224.
(92) Jap. Pat. 162,647 (March 8, 1944), Sakuragaoka Research Inst., Inc.; *C.A.*, **42**, 4201.
(93) U.S. Pat. 2,301,809 (Nov. 10, 1942), J. Lee.
(94) U.S. Pat. 2,319,094 (May 11, 1943), C. E. Truebe, G. S. Shahovskoy, and J. Levy (to Ernst Bischoff Co., Inc.).
(95) U.S. Pat. 2,325,681 (Aug. 3, 1943), O. Isler (to Hoffmann-LaRoche Inc.).
(96) U.S. Pat. 2,331,725 (Oct. 12, 1943), R. W. Price and G. H. Carlson (to Lederle Laboratories, Inc.).
(97) U.S. Pat., 2,331,808 (Oct. 12, 1943), R. S. Shelton and M. G. Van Campen, Jr. (to The Wm. S. Merrell Co.).
(98) U.S. Pat. 2,334,669 (Nov. 16, 1943), G. H. Carlson and B. R. Baker (to Lederle Labs., Inc.).
(98a) U.S. Pat. 2,336,890 (Dec. 14, 1943), B. Riegel and P. G. Smith (to Abbott Labs.).
(99) U.S. Pat. 2,357,172 (Aug. 29, 1944), G. H. Carlson and B. R. Baker (to Lederle Labs., Inc.).
(100) U.S. Pat. 2,367,302 (Jan. 16, 1945), M. B. Moore and F. J. Kirchmeyer (to Abbott Labs.).
(101) U.S. Pat. 2,372,655 (April 3, 1945), M. Bockmühl, O. Schaumann, E. Bartholomäus, and H. Leditschke (to Winthrop Chem. Co., Inc.).
(102) U.S. Pat. 2,383,392 (Aug. 21, 1945), W. Karrer (to Hoffmann-La Roche).
(103) U.S. Pat. 2,402,226 (June 18, 1946), J. Hyman and C. F. Peters (to Velsicol Corp.).
(104) U.S. Pat. 2,407,823 (Sept. 17, 1946), L. F. Fieser (to Research Corp.).
(105) U.S. Pat. 2,428,253 (Sept. 30, 1947), F. von Werder, Vested in the Attorney General of the U.S.

RALPH F. HIRSCHMANN

VITRAIN. See *Coal*, Vol. **4**, p. 96.

VM&P NAPHTHA (VARNISH MAKERS' AND PAINTERS' NAPHTHA). See *Petroleum (products)*, Vol. **10**, p. 167; and such articles as *Coatings, industrial*; *Paint*; *Varnishes.*

VOLATILE OILS. See *Oils, essential.*

VOLUME MEASUREMENT. See *Fluid mechanics (flow measurement).*

VOLUMENOMETER. See *Density and specific gravity*, Vol. **4**, p. 892.

VOMICINE, $C_{22}H_{24}N_2O_4$. See *Alkaloids*, Vol. **1**, p. 498.

VULCANIZATION; VULCANIZING AGENTS. See *Rubber chemicals*; *Rubber compounding and fabrication.*

W

WAD. See *Manganese and manganese alloys*, Vol. 8, p. 722.

WALDEN INVERSION. See *Stereochemistry*, Vol. **12**, pp. 861, 889.

WALLBOARD

Classification ..... p. 875
Hardboard and semihardboard 876
Other wallboards 885

Classification

The word "wallboard" has become a general term applied to large boardlike materials used on or as a wall. It has been applied in some instances to mean a single kind of board, but those in the building business, and others, have come to recognize the term as a general classification. Usually excluded from the accepted meaning of the word are built-up combinations of materials. These are referred to more often as "panels" although plywood and gypsum board, well-known wallboards, are in a way laminated products. This article also deals with related materials that might be described as "building board" since their use is not necessarily on or in a wall.

Wallboards, in the broader definition, are classified in major types below. Eliminated are boards in minor use and those that would be called panels or some other name. Among those excluded are plastic panels, metal panels, laminated wood fiber products, laminated corrugated panels, and the like. Finishes are not considered in this classification because most wallboards have a variety of surfacings.

Table I gives a general classification of wallboards.

TABLE I. General Classification of Wallboards.

Organic	Inorganic-organic	Inorganic
Hardboard	Gypsum wallboard	Asbestos-cement
Semihardboard	Wood–inorganic binder	
Insulating board		
Plywood		

The division between organic and inorganic-organic wallboards is not entirely sharp, since organic boards use a small proportion of inorganic chemicals such as alum, sulfuric acid, or sodium aluminate in the sizing operation.

Table II shows characteristic ranges of density and thickness of organic wallboards.

Inorganic-organic wallboards can be classified into two broad types; the first, a laminated wallboard in which the organic material is applied to the surfaces and the core is inorganic; and, second, the wallboard containing both organic and inorganic

TABLE II.

Type of board	Density, lb./cu.ft.	Thickness, in.
Hardboard	50 to 70	1/8 to 5/16
Semihardboard	30 to 50	1/4 to 1
Insulating board	10 to 30	3/8 to 1
Plywood	20 to 40	1/8 to 1 1/4

constituents blended together throughout the board. The widely used gypsum wallboard is an example of the first type, and the wood excelsior–inorganic bonded board, the second.

Asbestos–cement wallboards are the only completely inorganic wallboards in general use. While there are several types of "cement" used in these boards in combination with the asbestos fiber and a variety of densities, they have similarity enough to justify the single classification. Excluded from this classification as noted above are metal panels.

Hardboard and Semihardboard

Hardboard was first developed by William H. Mason in 1926 in the United States. Mason, a former associate of Thomas A. Edison, turned his attention to the utilization of wood waste following successful development of processes for recovery of turpentine, rosin, and pine oil from sawn lumber. He was familiar with the softening effect of steam on wood and began experimental work to combine this action with a method of rupturing the fiber bond by explosion with high-pressure steam. He found it necessary to go to a pressure of 1000 p.s.i. in order to obtain the proper degree of fiber liberation after a lower-pressure steaming time to soften the fiber bond.

This exploded fiber was a brown, fluffy mass which is known as gun fiber. It was found to be very well suited for the manufacture of structural insulation board, and his first attention was turned towards this market. However, experimental work proceeded along the lines of developing a high-density, small-thickness building board. After numerous failures, he found that by correct simultaneous application of heat and pressure to a sheet formed of these fibers, a highly dense, strong, and water-resistant product could be made. The product was given the name "Presdwood" and Mason originated the trade name Masonite and founded the largest hardboard producer, The Masonite Corporation.

The Masonite process spread abroad and was used in Sweden's first hardboard plant in 1929. Since that time it has been used for about 80–90% of the world's production of hardboard.

Almost all of the types of fibrous hardboards have similar properties. The requirements for 1/8-in. hardboard in Federal Specification LLL-F-311, Fiberboard: Hard-pressed, Structural (July 12, 1940), Federal Standard Stock Catalogue, are given below:

Material	Density, lb./cu.ft.	Minimum modulus of rupture, p.s.i.	Maximum water absorption (24 hr. immersion), %
Class A (untreated)[a]	60	6000	20
Class B (treated)	60	1000	12

[a] *Note*: The difference between class A and class B is that class B boards have been surface treated in some fashion, for example, the board surface has been impregnated with drying oils.

Hardboard differs from the thick insulating wallboard (7/16–1 in.) by its greater density and rigidity, harder surface, and greater resistance to impact. Hardboards are thin boards made usually in 1/8–5/16 in. thickness, a 4 ft. width, and up to 16 ft. in length. They have a density range of 45–70 lb./cu.ft.

Hardboards are too thin and compact to be efficient heat or sound insulators, but are useful in covering partition walls; and, when sufficiently waterproof, they have been used for exterior surfaces.

In residential construction, hardboard is used in floors, ceilings, roofs, and interior walls. In nonresidential construction, it is largely used for concrete forms and interior partitions forming permanent parts of a building. On the farm, hardboard is adapted to many uses, such as exterior wall covering, partitions, and bins. In manufactured products also, hardboard has become increasingly popular in motor vehicle bodies, signs, toys, etc.

Consumption of building board of all types has grown more than tenfold since 1929, the bulk of the increase coming since the beginning of World War II. The greatest relative increase has been in hardboard; about 16 times as much hardboard was used in 1953 as in 1929. Increased interest in manufacturing hardboard is evidenced by the entry of two western hardboard plants in 1953 and six more in 1954. Hardboard production in 1952 was 1000 million square feet (1/8-in. equivalent), of which 220 was used in construction, 325 in furniture, 280 in manufacturing, and 175 in household uses (16).

The processes for the manufacture of hardboard can be classified as follows:

A. The wet process
   1. Masonite process
   2. Asplund process
   3. Miscellaneous wet processes
B. The semidry process—with addition of resin
C. The dry process
   1. With resin or adhesives
   2. With chemicals

THE WET PROCESS

Masonite Process. In the manufacture of the current leading hardboard product, Masonite's Presdwood, both hardwoods and softwoods are used, the former consisting largely of gum, magnolia, poplar, and other southern hardwoods and the latter of shortleaf and long-leaf pine. The wood is received at the plant in bolts 5 ft. long. All wood is purchased in the peeled condition, although rough wood may be used by modification of the process.

Softwoods and hardwoods are kept separated through the wood room and sorting operations and are then blended in proportions to give the desired properties in the finished product. Some of the products consist entirely of softwoods, others entirely of hardwoods, and some of mixtures of the two types of fibers, exploded separately, in the proper proportions to give specific results.

The explosion process used for fiber production is the subjection of the wood chips in "guns" to high steam pressures. The time in the "gun" is coordinated with the type of wood, the size of chips, and the moisture content. The entire cycle in the guns runs somewhat under one minute, including filling, preheating, bringing up to pressure, holding at pressure, and exploding. A steam pressure is used of 1000 p.s.i., equivalent to about 550°F. or 285°C. The time-temperature curve is extremely important, as

little as 0.5 second difference in the giving distinct changes in the fiber produced. A bottom discharge valve in the gun is instantaneously released and opened to the atmosphere, exploding the chips to fibers and fiber bundles. The fibers and fiber bundles enter a cyclone where the steam escapes; and the fiber and fiber bundles fall into a stock chest. From the stock chest, the fibers are carried by water and fed to a cylinder or Fourdrinier machine, similar to the standard papermaking machine, where the board is formed as a thick, continuous, fibrous mat. Excess water in the mat is eliminated by passing through squeezing rolls. In the formation into sheets, the softened fiber and fiber bundles become criss-crossed in various directions so that the resulting product is grainless and has substantially equal strength and stiffness in all surface directions. Usually, waterproofing agents are added to the fibers prior to their being fed to the Fourdrinier machine.

This thick wet lap is trimmed and cut to size, and the individual pieces are conveyed on a wire-covered steel plate to the deck loader of the hot press. The hot press usually has twenty openings and is capable of pressing sheets 4 ft. wide and from 8 to 16 ft. long. The pressing conditions for hardboards $\frac{1}{8}$–$\frac{5}{16}$ in. thick are: time, 8–20 minutes; pressure, 1,000 p.s.i.; temperature, 350°F. As the hot platen press is being loaded from one end, the unloader at the other end removes the finished board. The "cured" hot, dry hardboards are trimmed and then humidified at about 80% relative humidity usually using atmospheric pressure steam. The resultant board has a brown color and is smooth on one side with screen marks on the other. Often the hot, dry hardboards when removed from the press may be further heat-tempered by oven-baking or may be tempered by dipping in a drying-oil bath (which may contain resins) and then heat-treated to cure the drying oil–resin mixture.

Asplund Process. The principal difference between the Masonite process and the Asplund process is in the means of obtaining the individual fibers. In the Masonite process, the individual fibers are obtained from the sudden explosion of the wood chips from the "guns"; in the Asplund process the individual fibers are obtained by the use of an Asplund defibrator.

The basic principle of the Asplund process is the heating of wood or lignocellulose materials to a temperature of 150°C. and higher in the presence of 150–160 p.s.i. steam pressure. This has the effect of softening the so-called "middle lamella" (high lignin fraction) which binds the individual fibers together. This softening action starts immediately at temperatures above 100°C., but is most pronounced above 150°C. In this condition the fibers can easily be rubbed apart at low power cost. The chips (not fine sawdust, or shavings, etc.) are introduced into a horizontal preheater of the Asplund Defibrator by means of a reciprocating plunger or screw feed. Chips are compacted in the so-called plug pipes where they form a seal against steam. As chips arrive in the preheater, the plug of the chips breaks up. Heating of the wood chips in a steam atmosphere of 160 p.s.i. pressure takes only a short time—usually about one minute. From the preheater, chips are carried to defibrating disks where fiber separation takes place. Fiber thus made is discharged into the open air by means of a valve system, which consists of two valves operating between a discharge chamber. This chamber becomes filled as the first valve opens. Shortly after the first valve is closed, the second valve is opened and the pulp and steam contained in this discharge chamber is blown out into a cyclone. Water is sprayed into this cyclone, which condenses the steam and forms a water suspension of fiber. From this stage of the operation succeeding steps are similar to that described above for the Masonite process.

These steps include refining, screening, and other preparation of the fiber; the slurrying of this and making of wet lap on a Fourdrinier machine; and the final pressing of the wet fibers.

In the case of boards made by the Masonite process, there is no use of resin or binder, and only waterproofing agents are sometimes added. On the other hand, the use of a small percentage of phenolic resin precipitated on the fibers has been the general practice in the Asplund process for many years.

Miscellaneous Wet Processes. A variation of the continuous wet process is the *batch wet process*. Wood chips of the size used in paper manufacture are reduced by attrition or Asplund defibrators to a fibrous mass which is mixed with a small percentage of phenolic resin. The stock, a mixture of water, resin and fibers, is metered into a deckel box, where the water is drained off through a screen instead of onto a continuous screen belt. The ensuing steps needed to make a hardboard are similar to those used in the continuous wet process. In this case the product is also brown in color and smooth on one side.

Equipment such as chippers, defibrators, high-pressure boilers, washers, and presses, besides all the special handling and loading machines needed in any wet process, are expensive. This high cost of breaking whole wood down into its individual fibers and fiber bundles and the attendant complications and skill required in the subsequent operations means that the making of wallboard by the wet process must be a very large business enterprise.

About the middle of 1952, the Oregon Lumber Co. placed on stream a hardboard plant which successfully utilized 30–50% of various barks, including Douglas fir, white fir, and western hemlock, with defibrated wood chips. The use of bark provided the hardboard with satisfactory moisture resistance and dimensional stability and eliminated the use of all other chemicals.

THE SEMIDRY PROCESS

The outstanding difference which exists between the semidry process and the continuous wet process, is that no water is used to carry the fibers during the forming operation. In order to produce the same quality of board by this process as by the wet process, the addition of resin is always necessary. In many instances, if a sufficient quantity of resin is added, the final board can be made equal in most respects to the boards made by the wet process. The plant investment for the semidry process is considerably smaller than for the continuous wet forming process and compares favorably with the wet batch process.

The flow line for a typical plant would begin at the truck deck where chipped wood is brought to the chip bin. From the chip bin, the wood chips are carried by conveyer to the cooking section for a short cook prior to entering a fiberizing machine. After the cooker, the resins and other waterproofing materials are added, and the fibrous material, which contains about 50% moisture, is carried into the grinder. From the grinding machine the fibrous material, which now has about 20% moisture, is carried to the felter where it is laid down as a continuous felt, or it can be laid down in a batch system. Directly from the felting machine the material is carried mechanically to the press loader and from there on to the hot press for an appropriate pressing cycle. It is finally removed from the hot press to the panel receiving rack and conveyed to the humidification chamber. The humidification chamber relieves the stresses in the board by bringing it up to its equilibrium moisture content, so that the board will re-

main flat. From the humidification chamber, the board is put through the edge and end trim saw and is then ready for storage and packaging. The steps immediately following the pressing operation are similar to those described for the wet process.

THE DRY PROCESS

The dry process is so called because the wood particles or fibrous mat are fed to the hot, platen press in a dry state. If the board is self-bonded (no chemicals or resins or binders added throughout the process), the raw material is usually defibrated wood which is matted and cured in a press until the desired strength and density is obtained. If resins are added to the board, then the raw material is usually wood particles having a certain size and shape. In both instances, the final density of boards made this way usually places them on the borderline between semihardboard and hardboard.

Resin-Bonded Hardboard. The resins to be used can be added in either the dry state or the liquid state, depending on the moisture content of the wood particles and the particular resin used. Thermosetting resins of two types are used: phenol-formaldehyde and urea-formaldehyde. Other resins used in a small way are furfuryl alcohol condensed with a catalyst, melamine-formaldehyde, cresol- or resorcinol-formaldehyde, etc. The most popular resin used is phenol-formaldehyde. The phenolic resins are darker in color, somewhat higher in price, and give superior performance as compared to the urea resins. A typical flow line begins at the raw-material receiving station, which collects dry material from a planing mill or other manufacturing operation. Wet slab material from a saw mill, whole poles or trunks of trees, or cord wood, may also be handled.

The dry material goes directly through a chipper and into the chip bin, whereas the wet slab material may be, although not necessarily, first debarked, then chipped, and put through a chip dryer to bring it to the proper moisture consistency. The dry material is stored in a chip bin and then run through a grinder, usually a hammer mill or an attrition mill, to reduce it to the proper size. The material is then screened to the desired mesh size; and all coarse material is returned for regrinding.

From the stock bin the material is weighed and the resins and other binding agents or waterproofing compounds added in desired proportion and completely mixed, taking care that the distribution of fine and coarse material is kept in proper balance. Steel pans as cauls are filled and conveyed to the mechanical charger, onto the hot press for an appropriate curing cycle, and finally removed from the hot press to the panel-receiving rack and carried to the pan inverter where the board and pan are separated. There is a stock chest near the pan filler for holding as a back log material that has been mixed previously. From the pan inverter the board goes to the edge and end trim saw; the pans are carried back to the pan filler by a conveyor section. The boards are trimmed; processed through a sander to finish the surfaces if desired; and then sent to the board storage, packaging, and shipment.

The rapid growth of the dry process for making hardboard is due mainly to the comparatively low cost of production equipment, and the successful use of wood wastes and defective timber, and a wide range of species as the raw material.

The resin-bonded particle board made by the dry process differs from the standard hardboard made by the wet process in the method of fiber preparation—affecting the size and shape of the woody particles, and the use of bonding agents to hold the wood particles together. The wood particles of the resin-bonded particle boards are generally larger in size, and somewhat granular in shape.

Hardboard Made with Chemicals. Since 1947, Smith, Othmer, and Ricciardi have developed a dry wallboard process using neither resins nor conventional binders, and have brought the process to the pilot-plant stage. Basically this process consists of the addition to and thorough mixing of a small amount (usually about 6%) of inexpensive chemicals such as sulfur, lignin, silicates, and homologs of phenol with the fine wood waste, the pressing of this mixture in a heated press at about 500–700 p.s.i., and the withdrawal of the board so formed in about ten minutes. The operation is done without the expensive evaporation of all of the water still retained in this step in the wet process, and the preliminary treatments are comparatively simple. The plant required is low in capital cost and the manufacturing process may be almost entirely automatic.

The process depends on "reactivating" the lignin. Up to 2.5% sulfur has been shown to unite with the lignin present in the wood, under the conditions of the pressing operation, that is, high temperature and possibly moisture. A new compound with lignin is formed; and this bonds together the granular or fibrous material. Similarly, sodium silicate combines with lignin. Its action here is entirely different from its usual adhesive use as water glass. While some wood species contain sufficient lignin to give this desired effect, others do not. For these, more lignin may be added, in the form of low-valued material recovered from the pulp and paper industry. These low-cost additives make strong, hard, water-resistant boards of wood waste, bagasse, etc., without the use of the much more expensive resins. The combination of sulfur has the additional advantage of making the boards very resistant to rot, molds, termites, etc.

Sawdust and shavings are collected at the central storage bin, and tramp iron is magnetically separated. From here the raw material is screened, the coarse material passing through a hammer mill, the fine material through an attrition mill. Both hardwoods and softwoods may be used. The two streams of fine fibers are blown to an elevated bin. If fibers are prepared by a combined steam and mechanical defibrating action, they may be used instead of ground particles to make an excellent board. The mixture is loaded by machine into trays. The filled trays are then loaded automatically into a hot press with as many as twenty openings, by means of conventional elevators and pushing devices. The chemical reactions of re-forming the wood are all accomplished in about ten minutes, while pressure is applied at the operating temperature. The wood-chemical mixture, slightly more than 1¼ in. deep, usually is compressed under heat and high pressure to a final thickness of about 3/16 in. The

TABLE III. Physical Properties of Wet-Process Masonite Products.

Property	Presdwood ⅛ in. thick	Tempered Presdwood ⅛ in. thick
Sp.gr.	1.03	1.10
Modulus of rupture, p.s.i.	6,200	11,000
Modulus of elasticity, p.s.i.	550,000	850,000
Tensile strength, p.s.i.	3,200	5,100
Rockwell hardness, R scale	48	75
Water absorption, % uptake in 2 hr.	5.5	—
Water absorption, % uptake in 24 hr.	16.0	11.7
Water absorption, % uptake in 48 hr.	—	15.6
Heat transmission coefficient, B.t.u./(hr.)(sq.ft.)(°F./in.)	1.35	1.50

resulting board so formed is hard and strong but somewhat plastic at the high finishing temperature. Its maximum strength develops within a few hours. It is cooled, humidified, and trimmed to standard sizes. From there on it is handled as normal lumber.

PHYSICAL PROPERTIES

Physical properties of two commercial hardboards now on the market are given in Tables III and IV.

TABLE IV. Physical Properties of P.V.[a] Brand Semidry Resin Process Wallboard.

Properties	1/8 in.	3/16 in.
Weight, lb./sq.ft.	0.715	0.960
Sp.gr., vol. at test, wt. oven-dry	0.90	0.89
Modulus of rupture, p.s.i.	6136	6568
Tensile strength, p.s.i.	—	—
Water absorption, % uptake in 2 hr.	5.79	5.23
Water absorption, % uptake in 24 hr.	17.6	16.13
Thickness increase, % in 2 hr.	1.84	1.56
Thickness increase, % in 24 hr.	10.88	9.68
Heat transmission coefficient, B.t.u./(hr.)(sq.ft.)(°F./in.)	5.6	4.2

[a] Canadian Forest Products Ltd.

SEMIHARD BOARD

Fibrous Board. Building fiber boards of this intermediate classification include boards weighing between 25 and 50 lb./cu.ft. They are sometimes called hardboards, but the term "semihard" or "intermediate density" is more descriptive. The large range in strength and other physical properties for semihard board is shown below:

General classification	Thickness, in.	Sp.gr.	Modulus of rupture, p.s.i.	% Water absorption, 24 hr. full immersion
Semihard fibrous board	3/16–1/2	0.4–0.8	400–4000	—
Semihard particle board	1/4–3/4	0.4–0.8	400–1000	100–150

The primary use for semihard fibrous board is for interior wall covering. Because they are denser than the rigid insulation boards, they usually have more resistance to abrasion or other surface damage than lower-density boards. These boards also have limited use in furniture manufacture. They can be used to advantage as drawer bottoms and dividers in chests, as backs in cabinets and similar items, and as core stock in utility-grade furniture. When used as paneling, they may be cemented or nailed in place. Standard woodworking tools can be used for fabrication. The boards take and hold paint well, although the surfaces sometimes must be sealed to prevent paint from soaking into them.

Semihard fiber board can be manufactured by any one of the wet process methods or the semidry method previously described in the section under hardboard. In general, the main differences are (*1*) an increase in the original thickness or weight of the fiber mat used, (*2*) a lower platen pressure, and (*3*) a longer time of pressing.

Semihard Resin-Bonded-Particle Boards. This type of board provides a profitable way to utilize residues from millwork, furniture, or similar operations. It is used as an interior paneling in houses and in furniture and millwork. Because the semihard resin-bonded-particle boards stay flat with changes in moisture content, they are used

as alternates for solid lumber cores in veneered construction. The linear expansion with changes in moisture content may be large, but it is not greater than the values for wood across the grain.

The method of manufacturing this type of board is very similar to the dry process except for the increase in pressing time, decrease in platen pressure, and increase in original thickness or weight of original dry mat.

Specialty Boards. A great variety of specialty boards of various types have been developed experimentally and commercially throughout the world.

Novopan. This product is a batch dry-process resin board consisting of a granular low-strength core surfaced on both sides with prepared shavings of high resin content, giving a pearly effect to the surface. The core represents 84% by weight of 1-in. board and 60% by weight of ¼-in. board. The core and surface are formed and pressed simultaneously. Thicknesses range from ¼ to 1⅝ in. This board has been commercially produced in Switzerland since 1945. The U.S. Plywood Corporation has built a plant to make this type of board in California.

Solid wood scrap for core material (2–3% moisture content) is ground to about 0.2 in. particle size and screened. Surface shaving material is prepared from large undried blocks of wood 6 in. or thicker, mill ends 1 in. or thicker, or 6–14 in. logs, using specially developed shavers. Core and texture materials are fed automatically from bins to automatic scales and then to formers where the separate layers are automatically spread into forms. The forms are fed into the press. After pressing, boards are edged and trimmed.

Total resin content (urea formaldehyde) is less than 10%.

CTH Board. This is a dry-process batch-resin semihard board using urea-formaldehyde resin, and developed by the Chalmers Tekninka Hogskola, Goteborg, Sweden. Shavings, cuttings, and sawdust (10–15% moisture content) are ground. Fibers smaller than 0.118 in. are discarded. The raw material is sifted and resin is added, and the charge is automatically weighed and passed to the forms. The molds are hydraulically pressed using high-frequency current for heating. The boards are removed and cut to size. The surface is lightly ground and buffed. A minimum moisture content is required in the raw material for effective use of high-frequency heating in the press.

Continuous Press Method (Bartrev Board). The Bartrev Co. of England has made semihard board, as well as other types, on a continuous hot press. It is believed that this press can produce board at the rate of 30,000,000 sq.ft. annually on a ⅜ in. basis, using more than 50 tons of normally wasted wood material daily, and producing a continuous 4-ft. wood panel at speeds up to 25 ft. per minute.

The raw material is reduced in size with a hammer mill (chipping machines are used if the material is in large pieces). It then goes to a storage bin, whence it is sent to the dryer. It is essential to maintain accurate control of the moisture content of the raw material at the point where it undergoes compression. The dryer must deliver a product with a constant moisture content whatever the initial content of the material.

The amount of resin used is about 6% on the raw material. The resinated material, in a layer of uniform thickness, is heated by radio frequency to about 75°C., and is then pressed in contact with platens which are heated to 140°C.

Extruded Board. The well-known particle cork board machine used for many years in the making of cork board has been adapted to the manufacture of wood-

particle wallboard. Thick boards are easily made in the extrusion machine, and these may have cored-out holes within the board. The extrusion method uses a resin-covered wood particle as in the other two methods, but employs a reciprocating ram to drive a measured volume of particles between two stationary converging hot surfaces. The converging surfaces provide frictional hold-back so that considerable pressure can be developed by the ram. The heat of the compressing surfaces serves to set the resin and consolidate the board.

An unusual and unique feature of the extruded particle board is the orientation of the longest dimension of the particle used. Unless all particle dimensions are nearly the same, the particle will orient itself as the ram drives it into place in such a position that the longer dimension is parallel to the ram face. This position of the particle results in good holding power when surfacing sheets are later glued to the board surfaces and also good holding power for edge driven fastenings. The board alone is quite flexible in one direction owing to the particle orientation.

The extrusion machines are comparatively small and low in speed with consequent low production rates. They are low in initial cost and so are attractive to small wood-working plants as an auxiliary operation for making core materials for sale or for self-use. The continuous 4-ft. wide sheets have the advantage of eliminating end and edge waste, and in addition the feature of closely spaced hollow tubes running through the sheet to reduce weight and material usage as well as aid in curing the resin during manufacture within the body of thick boards.

Bibliography for Hardboard and Semihardboard

HARDBOARD

(1) Anderson, A. B., and Runckel, W. J., *Paper Trade J.* (Jan. 25, 1952).
(2) Boehm, R. M., *Modern Plastics* (Oct. 1939).
(3) Boehm, R. M., *Paper Trade J.* (May 2, 1940).
(4) Boehm, R. M., *Tappi*, 331–34 (1944).
(5) *Federal Spec. for Fiber Board*, LLL-F-311.
(6) *Forest Products Lab. Rept.*, **1209** (1941).
(7) *Forest Products Lab. Rept.*, **R-1903-9** (1953).
(8) *Forest Products Lab. Rept.*, **D-1928** (1952).
(9) *Forest Products Lab. Rept.*, **1666-21** (1954).
(10) Lee, J. A., "New Products from Wood," *Chem. & Met. Eng.* (Feb. 1940).
(11) Masonite Co., *A Manual for the Product Designer.*
(12) Stanford Research Inst., *America's Demand for Wood 1929–1975*, 1954.
(13) "Wallboard Production and Uses," *Northeastern Wood Utilization Council Bull.*, **31** (1950).
(14) U.S. Pat. 1,399,976 (Dec. 13, 1921), G. J. Mason.
(15) U.S. Pat. 2,198,269 (April 23, 1940), H. K. Linzell and J. W. Gill (to United States Gypsum Co.).
(16) U.S. Pats. 2,537,101 (Jan. 9, 1951); 2,552,597 (May 15, 1951); 2,669,552 (Feb. 16, 1954); 2,687,556 (Aug. 31, 1954); 2,692,206 (Oct. 19, 1954), D. F. Othmer, L. G. Ricciardi, and W. R. Smith.

SEMIHARD BOARD

(17) "Chips to Board, Continuously," *Chem. Eng.*, 130–36 (Aug. 1953).
(18) Crafton, J. M., *Forest Products Research Paper*, **563** (1954).
(19) *Forest Products Lab. Rept.*, **1903-9** (1953).
(20) *Forest Products Lab. Rept.*, **1666-21** (1954).
(21) *Forest Products Research Soc. Ann. Proc.*, **2**, No. 5 (1952).
(22) "Medium Board," *Chem. Eng.*, 275–76 (Sept. 1953).
(23) Risi, J., *Pulp & Paper Mag. Can.*, **52**, 82 (Jan. 1951).
(24) "Wonderboard," *Wood Products*, 18–19 (Jan. 1949).

L. G. RICCIARDI

Other Wallboards

INSULATING BOARD

Insulating board is made in the U.S. and Canada by seventeen manufacturers. Of these seventeen, two are in Canada and three on the Pacific Coast. The balance are largely in the south central states. The annual production in the U.S. in 1954 was about 2.6 billion feet (square feet) based upon a ½-in. thickness. Insulating board was first made in 1914 by the Minnesota and Ontario Paper Company, International Falls, U.S. Production grew slowly until 1920, when the Celotex Company began production of insulating board at Marrero, Louisiana, from crushed sugar cane waste called bagasse. The Celotex Corporation is at present the largest producer of insulating board with an approximate annual production of three quarter billion feet. The Minnesota and Ontario Paper Company, Johns-Manville Corporation, and Armstrong Cork Company are also large producers.

Insulating board is the lightest of the wallboards and can easily be distinguished from the hardboards by its lower density and rigidity and its softer surfaces. Insulating board is also the only wallboard to furnish appreciable thermal insulation in rigid, large-board form. It is made in greater thickness than other boards for general production, ½ in. as compared to ⅜ in. in plywood and ⅛ in. in hardboard.

The distinguishing characteristic of insulating board is that the structure is maintained by a tangling of the fibers and by the cohesive effect of adsorbed water, rather than by the adhesion of plasticized lignin or of a resin additive. The structure formation of insulating board is largely reversible when soaked in water, but this is not true of self-bonded or resin-bonded hardboards. Therefore insulating board is subject to a much greater loss in strength when it is wetted.

Insulating board, although comparatively soft, is also quite resilient, and it has a good resistance to repeated rough usage not found in some of the inorganic fibers. Since it is a wood product, insulating board in the presence of moisture is subject to attack by microorganisms and insects. Treatments are available in manufacture that will protect the wood quite well from such attacks, but repeated exposure to moisture or insect attack or exposures of long duration will eventually deteriorate the board.

Insulating board is more susceptible to fire than the hardboards due to its lower density. A ½ in. thick square foot of insulating board will contribute about the same heat when burned as a square foot of ⅛ in. self-bonded hardboard or ¼ in. of particle hardboard. All wallboard and other interior wall and ceiling lining insulating boards are available with a flame retardant painted surface on the exposed side. Insulating board, when enclosed on both sides by air impermeable surfaces, does not have enough void space air to maintain burning or smoldering even in the lower density ranges. This is important in the case of insulating-board roofing insulations used on roof decks and under built-up roofing.

Raw Materials. Many types of organic fibers can be made into insulating board. Pulpwood was used by a majority of the fifteen manufacturers in the United States in 1954, but bagasse, extracted pine-stump waste, licorice root, and flax straw are also made into insulating board. In addition, a large quantity of waste newspaper and groundwood screenings from the manufacture of paper are used. The species of pulpwoods used are quite varied: jack, southern, and Virginia pines; Douglas balsam, and western firs; and hardwoods such as cottonwood, willow, aspen, tupelo, and sweet gum.

No resins or other additive binders are required in any quantity by the insulating board industry except asphalt which is a part of such products as exterior wall sheathing in the form of an integral mixture or as a coating. Raw or modified starch in small proportions provides slightly improved physical characteristics for some manufacturers. Wax and other sizing materials, such as modified rosins, are included by all manufacturers to reduce the affinity insulating boards have for water.

Manufacturing Processes. *Fiber Preparation.* Several processes are used in the manufacture of insulating boards. These divide basically into two processes, one mechanical and the other a combination of chemical and mechanical. In the *mechanical process*, logs are ground to a pulp on large, coarse pulp stones using pressure to hold the logs sideways against the surface of the stone and water sprays for cooling. The log bark is often removed before grinding. The pulp thus formed is diluted with a large quantity of water to a consistency of less than 1% and passed over screens. Rejects at the screens are reprocessed, and the accepted pulp is dewatered and rediluted to a specific consistency, often 3–5%, for sizing and storage in large chests preparatory to mat formation. Another process is chipping of the logs and reduction of the chips to pulp in a disk mill where rotating plates do the work. Not all woods are suitable for grinding. Those not suitable include most hardwoods, the exception being the soft hardwoods such as aspen, cottonwood, and willow. The use of saw mill waste such as slabs is hampered in the grinding operation by the difficulty and cost of bark removal and of handling such sizes and shapes.

The *chemical-mechanical process* is fitted for agricultural residues such as straw, bagasse, and flax straw, and for hardwoods that cannot be satisfactorily ground. The process consists of pressure-steam-treating the material in the presence of lime, sodium hydroxide, or neutral sodium sulfite. Five to ten per cent chemical on a dry weight basis is sufficient and one to two parts by weight of water. The cook serves to soften the material so that the fibers are more easily separated with less destruction. The next process is a mechanical rubbing and working of the material in a disk mill or other type of equipment that will produce a mechanical separation of the fiber. The fiber thus prepared is then treated in the same way as the ground wood fiber.

A variation sometimes used in fiber preparation is the Asplund process where the material is fed into a continuous cooker with or without chemicals and subjected to steam pressure for several minutes. The continuous cooker feeds the material still under pressure into a disk mill for reduction of the softened material to a coarse fiber. In the next step the coarse fiber no longer under steam pressure is passed to a disk refiner for further reduction toward fiber size.

A further variation recently come to the fore is termed "chemigroundwood," which is adapted to woods that cannot be ground in the usual way. This process is essentially that of ground wood, the only difference lying in the preparation of the pulp logs for grinding. The logs are loaded on cars which are run into a steam tank, much as in the creosoting process, and vacuum is applied. Next the chemical solution is injected and heat and pressure applied after which the pressure is removed and the available chemical solution drained off. Chemicals are the same as those used for treating chips. The logs are next removed, fed to the regular grinders, and reduced to pulp. The grinding may be done hot or cold any time after log treatment.

Pulp yields in the semichemical processes are about 84%, whereas the groundwood process gives about 94%. The semichemical process is accompanied by a more serious stream pollution problem than the ground wood.

In all fiber preparation methods, control and adjustment of pH must be made to apply size properly and to obtain a suitable pH at the forming machine. The addition of protective chemicals, such as sodium pentachlorophenate, may require further pH manipulation.

Forming and Drying. There are essentially two types of insulating-board forming machines; a cylinder type such as the Oliver board forming machine and the flat-wire or Fourdrinier machine similar to a paper machine. The cylinder machine is a hollow, wire-faced wheel turning partly submerged in a water suspension of the wood or other fiber. The wheel has a hub vacuum-valve system and is segmented so that a vacuum may be applied to assist sheet formation and mat dry-out, but can be cut off at the point where the mat is removed from the wheel. Fifteen to twenty inches of vacuum are frequently carried on these machines. The cylinder-type forming machine is generally preferred for insulating-board formation because of its ability to form a mat faster than the flat-wire types. However, a number of flat-wire machines are in use and have certain advantages over the cylinder machine such as simpler thickness control and uniformity and access of mat for wet end coatings.

The flat-wire machines are in effect moving horizontal wire belts upon which the water-borne fiber is spread. Dewatering is accomplished by gravity and by suction below the wire. Pressure may be used at the head box to accelerate stock deposition on the wire or by gravity head or pump.

After formation the wet mat passes between a top and bottom wire of a roller press for further dewatering and across a roller table to be cut into wet mats 16–24 ft. long. The mats are then placed in a roller dryer with a number of decks by a tipple system. Eight decks are common in such dryers allowing a speed approximately one-eighth that of the forming machine. The dryer heat is supplied by direct-fired gas, direct-indirect oil, or pressure steam. Dryers are built to take mats up to 13 ft. in width and are made long enough to accommodate the forming machine speed anticipated. Some of these light deck dryers are over 500 ft. long. Sheets are dried to 1 or 2% before leaving the dryer. A single line is formed upon emerging from the dryer which passes to the trim saws. The trim saws cut the large mat into smaller pieces, the 4 by 8 ft. size being the most common. After the trim saws, the sheets are rewetted to normalize their moisture content and placed in stock.

Finishing and Packaging. Treatment of the board from the trim saws onward depends upon the type of product being made and the degree of mechanization the manufacturer has applied to the operation. Coating of interior surfacing wallboard, for instance, is usually done by taking board from stock and running it through coating or painting equipment. In some instances the board passes directly from the trim saws to the painting operation emerging from the coater ready for packaging or working to other sizes and shapes. In the case of exterior sheathing, some manufacturers pass the sheathing directly from the trim saws to an edge-beveling machine and brand-printing press, while others stock-pile the blanks and later draw upon stock for the process from beveling on.

Sheathing, roofing insulation, and like items are not painted. Painted items are passed through a roll or spray coater, coated one side, and dried. Speeds above 100 linear feet per minute are sometimes used in the coating operation. The paints are water-vehicle types of a greater or lesser degree of washability and are all flame-retardant. Most insulating board products are packaged by carton or wrapping.

Loose shipments are occasionally made in carload lots of items, such as sheathing or roofing insulation.

Products, Specifications, and Standards. Standards, specifications, and testing methods bearing upon insulating board are listed below: (*1*) "Structural Insulating Board from Vegetable Fiber," A.S.T.M. Designation C208–46T and C209–46T. (*2*) "Fiberboard: Insulating," Federal Specification LLL-F-321b. (*3*) "Structural Fiber Insulating Board," Commercial Standard CS 42-49, U.S. Department of Commerce. (*4*) "Structural Insulating Board (Wood or Other Vegetable Fiber)," Simplified Practice Recommendation R179-46, U.S. Department of Commerce. (*5*) "Homogeneous Fiber Wallboard," Commercial Standard CS 112-42, U.S. Department of Commerce. (*6*) "Water Vapor Permeability of Sheet Materials Used in Connection with Thermal Insulation," A.S.T.M. Designation C–214–47T. (*7*) "Acoustical Units: Prefabricated," Federal Specification SS-A-118a. Used for fire tests. (*8*) "Paint, Fire-Retardant, for Interior Fiberboard Surfaces," Navy Department Specification, General Specification for Inspection of Material MIL-P-11297(CE). (*9*) "Fiberboard Undercoursing for Wood Shingles," FHA Bulletin No. UM-14. (*10*) "A Standard for Testing Sheathing Materials for Resistance to Racking," FHA Technical Circular No. 12.

The six classes of insulating board made, and thicknesses obtainable, are shown in Table V (2).

TABLE V. Insulating Board Products, Classes, and Thicknesses.[a]

Type of board	Class	Thicknesses, in.
Building board	A	½, 1
Lath (for plaster base)	B	½, 1
Roof-insulation board	C	½, 1, 1½, 2
Interior board (factory-finished)	D	½, ¾, 1
Sheathing	E	½, 25/32
Interior board (flame-resistant surfaces)	F	½, ¾, 1

[a] Abstracted from Commercial Standard CS-42-49.

Uses. The major uses of insulating board are three in number: residential frame sheathing, industrial insulation under built-up roofing, and interior residential surfacings.

Residential insulating board exterior sheathing is light in weight, gives a frame wall good racking strength, goes up rapidly, and provides extra thermal insulation. It is durable, has a good moisture vapor permanence, and has no knotholes or cracks. During World War II, considerable impetus was given the use of insulating board sheathing due to a scarcity of lumber sheathing. It now represents about one quarter of the market and has continued to increase in per cent of the market sold since the war. The use of integral and coating asphalts, introduced in insulating board sheathing since the war, materially improved the product and assists in maintaining and extending its market.

The second large use for insulating board, roofing insulation, is a recently developed use for the product. It has grown rapidly due to the increased recognition roofing insulation has received in nonresidential construction. The popular thickness is 1 in., but thicknesses from ½ to 2 in. are standard. Special low-density grades are made to improve thermal characteristics. The board is fastened down to the roof

by asphalt mopping or nailing. Frequently a water vapor barrier is placed below the insulation to prevent condensation taking place in the insulation. The waterproofing felts are applied to the top of the insulation by mopping.

The third large use of insulating board is for surfacing interior residential buildings. A large variety of sizes, shapes, and colors are available in the ceiling tile, wall plank, and square-edged sheets. The boards are all factory painted with flame-retardant paints. A lath is also made and used as a plaster base. Interior surfaces are nailed in place with wire nails or staples. Applications of acoustical tile are sometimes made over plaster with adhesives.

There are many other uses for insulating board, which include insulated siding, acoustical tile for sound control, die stock for the shoe industry, roof plank for flat roof residential work, formboard for pouring light-weight concrete or gypsum roof decks, cushioning material for packaging, and sound deadening in metal shapes.

PLYWOOD

Plywood is a well-known wallboard and is used extensively in the building industry. Plywood, as the name indicates, is made up of thin layers of wood cemented together with a suitable adhesive. It has reached its present market volume of 4–5 billion square feet, ⅜-in. basis, due to its light weight, strength, and workability. Widths up to 4 ft., and lengths to 12 ft. are easily obtainable. Thicknesses range from ⅛ to 1¼ in. with the popular wallboard thickness at ⅜ in. The ⅜-in. thickness is also used as a basis in figuring annual productions, just as a ⅛-in. thickness is used in the hardboard industry and ½-in. in insulating board.

Residential use of plywood was aided by the development of exterior-grade plywood in 1934 for exterior walls. In 1954, about 40% of the plywood used in new residential construction was for roof sheathing, 25% for sheathing on exterior wall surfaces, and 18% for floor underlayment. Plywood in 1954 represented about one quarter of the roof sheathing market.

Plywood wallboard is used in nonresidential construction, also principally for concrete forms. Hardwood plywood wallboard is frequently used as interior paneling.

See *Plywood.*

GYPSUM BOARD

The manufacture of tile and board from calcined gypsum (see Vol. **2,** p. 767) is an old art. Wallboard products started about 1903 with the production of lath. Lath was followed in 1917 by the development of wallboard in the 4-ft. widths, up to that time considered too difficult for manufacture. Ten years later, the use of gypsum was extended to residential sheathing in a 2 ft. by 8 ft. by ½ in. size with interlocking long edges. Annual production has increased year by year, until in 1954 total sales of lath and wallboard reached a total of about 6 billion square feet. The largest manufacturer of the many well distributed throughout the U.S. is the United States Gypsum Company with the National Gypsum Company next largest.

The popular sizes in gypsum wallboard are 4 ft. by 8 ft. by ½ in. or ⅜ in. wallboard and 16 in. by 48 in. gypsum plaster base (lath) board. Wallboard may be obtained in lengths from 6 to 12 ft. and in thicknesses of ¼ to ⅝ in., lath in ⅜ and ½ in. Gypsum wallboard is also made with a tapered or square long edge and with plain or decorative surfaces. Both are also made with reflective insulating back surfaces.

Gypsum board like asbestos-cement wallboard gains workability, toughness, and

strength by the addition of a tough fibrous element to a hard, brittle base material. The gypsum board differs from the asbestos-cement product, however, in two important ways. First, the fibrous element of the gypsum board is concentrated at the surfaces, while in the asbestos-cement the fiber is distributed throughout the mass; and second, the fibers of gypsum board are organic, while those of the asbestos-cement sheet are inorganic asbestos fiber.

A unique feature of gypsum wallboard is the small change in the size of the board produced by changing moisture content. When a wall surface is covered with large wallboards and the wallboards are fastened together at the joints with a rigid connection, the joint strain is a product of the cross-sectional area, elasticity, and moisture movement of the wallboard. The low moisture movement of the gypsum board results in low joint strain when adjacent sheets are fastened together by a rigid joint treatment or all-over plaster coat. This led to the development of a locked joint system, where hydraulic setting, plaster-like putty combined with a reinforcing cloth or tape fastened adjacent sheets together producing an apparently continuous surface. The United States Gypsum Company's Perf-A-Tape system is one such treatment and National Gypsum's Gold Bond Tape system is another. Such "taped joint" systems have become popular for finishing interior surfaces and are gaining in use displacing the more costly plaster.

Several improvements increased the performance of the gypsum boards and their use. Lath was perforated with ¾-in. holes to increase plaster bond and fire rating, reflective insulation was made available on the back of some types of boards, improved papers were supplied for exposed board surfaces, and a sheathing core of improved water resistance produced by the use of the water contained in emulsions of asphalt to set the gypsum of the core.

Gypsum boards are rather heavy as wallboard products go, having a weight of about 2 lb. per square foot in a ½-in. thickness. A ⅜-in. thick interior surfacing board 4 by 8 ft. weighs about 48 lb. Sheathing which is ½ in. thick is reduced in size to 2 by 8 ft. and a weight of about 33 lb. per sheet for easier handling. Gypsum also has a tendency to soften when wet. In interior wallboards this characteristic is not important, but outdoor use of unprotected gypsum sheets is usually avoided.

Specifications for gypsum wallboard and lath are as follows: A.S.T.M. C36–42, gypsum wallboard; A.S.T.M. C37–42, gypsum lath; A.S.T.M. C79–42, gypsum sheathing; Federal Specification SS-P-431(1), gypsum plaster board; Federal Specification SS-P-402(1), gypsum plaster.

Raw Materials. The surface of gypsum lath and wallboard is a wood fiber paper made especially for the purpose. The paper must have a degree of absorption so that adhesion is developed between the paper and the core during manufacture. It is believed the crystals of the dihydrate, formed during setting and hardening of the gypsum, interlock with the fibrous structure of the paper and provide satisfactory adhesion. Usually adhesives are not necessary to hold the paper to the gypsum core, although sometimes starch or casein admixtures are added to the mixing water to improve the paper bond. The paper used on the surface of wallboard, to be exposed later on the wall surface, is often a smoother, lighter-colored paper. These special surface papers improve the appearance after application to the wall and make a superior base for paint or paper. An overlay of decorative papers or veneers is sometimes applied to the finished dried board.

The core of gypsum board is made from commercial calcined gypsum to which

has been added 10% or less of sawdust or some other fibrous material to lighten the core. Water is added in measured proportions to the powder weight to effect the hydration. Entrainment of small quantities of air has also served to reduce core weight. Small quantities of other materials such as casein, starch, and asphalt may be added to the gypsum core to improve characteristics of the core.

Manufacturing Process. The manufacture of gypsum wallboard has one unique and difficult problem: the rapid hardening that takes place in forming with calcined gypsum and the consequent build-up of hardened gypsum, which is an accelerator for the hardening reaction, on all equipment with which the putty comes in contact. The rapid hardening is a two-sided effect, however, for it also provides a rapid process that lends itself to large-scale production. The forming problem was solved by the universal use of a continuous paper band upon which the gypsum "mud" is deposited, spread out level, covered with a top sheet of paper and allowed to set. In this way all forming equipment is kept clean, and sticking of the core gypsum is avoided.

Methods for the preparation of the gypsum core ingredients and subsequent mixing with water vary from mill to mill. Some use mixers of various familiar types to blend the powders and water, while other mills mix in the water on a mixing belt. The mixing belt can be kept clean with squeeze rolls and water sprays more easily than a batch mixer. However the core slurry is prepared, it always reaches a point where it is spread on a moving band of paper whose edges have been turned up to prevent edge escape of the gypsum slurry. After deposit on the paper, the slurry is smoothed out to a uniform spread across the paper, edge to edge.

Next, the edge paper is again folded into the slurry of the core and a top paper applied. Further smoothing of top and edges then takes place to assure proper thickness and edge shape. The tapered edge can be applied at this point or the "V" grooved edge of sheathing.

The gypsum wallboard or lath is now formed in an endless board. Long roller tables next allow time for the gypsum core to set and harden. The roller tables are often parallel to the drier, but travel of the board is in the opposite direction. Forming speeds as high as 100–150 ft. per minute are used so that even though the set table may be 400–500 ft. long the set time is not long. Dryer temperatures have been increased until now temperatures may be 400°F. or more. Upon leaving the dryer, the board is cooled, packaged, or further processed and placed in stock.

The gypsum wallboard process, like many other continuous processes, is simple in principle, but leads to numerous control and mechanical problems. The synchronization and quantity-of-ingredients control problems are complicated by time of set in the gypsum. The amount of colloidal retarder required in the gypsum core varies from mill to mill and sometimes in a single mill where variations occur in the impurities present in the gypsum.

WOOD–INORGANIC BINDER

Wallboards composed of wood particles or strands cemented together with inorganic binders have a limited but growing production in the U.S. In Europe the production of this type of wallboard is far more extensive due primarily to competitive factors. Germany alone has nearly 300 manufacturers in the business, most of them small producers for local consumption. The U.S. had nine manufacturers in 1954 with a comparatively small total production.

Wood is used as an aggregate in cement, replacing the normal aggregates of stone

or sand, to obtain a material of lighter weight, greater toughness and strength, and much better workability. The wood aggregate is largely of the wood strand or excelsior type, although much shorter strands that have better forming properties in manufacture are sometimes employed for the purpose. Sawdust and other granular wood particles do not produce sufficient strength to compete with the strand aggregate for the manufacture of wallboard. Owing to the physical properties resulting from the strand wood aggregate, the material can be formed into relatively thin sheets and is suitable for many wallboard purposes. Each strand of wood is coated with the inorganic binder and thus protected from microorganisms that destroy wood, and to some extent from fire. The rough surface customarily produced provides large surface voids. These voids give an excellent key for stucco or plaster application, or, if uncovered, a good degree of sound absorption. The wood aggregate is of sufficient size to hold nails nearly as well as solid wood. Sawing and cutting is not as easily done as in solid wood and tends to dull carpenters' tools. The cut ends and edges are rough and sharp to handle due to the size and stiffness of the wood strands. The board is, however, classed as "workable" in that it is not seriously difficult to work with carpenters' tools.

Inorganic-wood strand wallboard is made by processes that lend themselves to large- or small-scale manufacture by hand methods. This unusual fact has resulted in the widespread, small-scale manufacture in Europe.

The inorganic-wood strand wallboard is made in 20–48-in. widths and 48–96-in. lengths. The popular thickness is 1 in., but ½–3-in. thicknesses are obtainable. The density varies from 24 to 42 lb./cu.ft., the thermal conductivity from 0.45 to 0.55 B.t.u./(hr.)(sq.ft.)(°F./in.), and the noise reduction coefficient may be as high as 0.60.

Raw Materials. The inorganic binders are many and varied. The principal binders are portland cement, calcined gypsum, magnesite, magnesium oxychloride, and magnesium oxysulfate. A binder that hardens rapidly is preferred because of the simplified process that results. The magnesium binders are somewhat limited in availability in certain areas, but gypsum and portland cement are generally available. The ratio of binder weight to wood weight ranges from 2:1 to 3:1.

Wood excelsior of widths up to ¼ in. and thicknesses up to $\frac{1}{10}$ in. is the principal aggregate. The fiber excelsiors are preferred for acoustical boards and some wallboards because they produce a smoother appearance. The wood itself is of many species depending upon availability and compatibility with the inorganic binder. Certain woods containing acids and soluble sugars, for example, are unsuitable for use with a portland cement binder. Very small amounts of wood sugars will retard or completely inhibit the hardening of the cement. Thus a slight hydrolysis of gums or hemicelluloses may be responsible for unsatisfactory results. Oak, southern pine, and larch are not suitable for a portland cement binder, while cottonwood, aspen, ash, and gum give good results. Treatment of unsuitable woods chemically or by cooking or washing does not often improve their characteristics, and increases costs.

Excelsior has an undesirable springy quality plus a tendency to tangle and lump. The springiness presents a problem in manufacture due to the difficulty in maintaining the compressed thickness necessary for smoothness and density. The net result is the cement-covered, wood-strand mat must be held under pressure until the cement has gathered enough strength to maintain the compressed state. To avoid maintained compression, some makers have tried to reduce the length of the excelsior strands.

This has resulted in some decrease in the difficulty of mixing and spreading the strands; but these benefits are accompanied by some loss in strength, and maintained compression is still necessary although shortened.

A further change in the wood particle shape has been made in Europe. Wood in the form of kraft pulp is combined with inorganic binders. Often asbestos fiber is included as well. In this case formation is done by a wet-felting machine and repress. The problem of spring-back is eliminated because maintained pressure is not necessary during curing. A wallboard of the kraft fiber type is that made by Eternit, S.A., Belgium, known as Emsen board. An example of excelsior board made in Germany with a magnesium oxysulfate binder is the Herkalith board made by the Herkalith Company. In the United States an excelsior board with calcined gypsum binder, Tectum, is made by the Alliance Manufacturing Company, Ohio, and a portland cement-excelsior board, Cemex, by the Cemex Corporation, Illinois.

Manufacturing Processes. The manufacture of wood–inorganic binder boards is quite varied, no two processes being alike in more than a general way. This is due to the variation in the requirements of the binder, type of wood aggregate, availability and cost of labor, and the size of the market. The largest group having similar manufacturing methods is that of the makers using excelsior aggregate. Variations are present in this group also, but the processes are basically similar. All begin with excelsior, untangle it to some extent, then apply the inorganic binder. There are many ways in which the binder is applied to the excelsior. One method wets the excelsior with water and causes it to fall through a suspension of dry cement in air; another tumbles the wet excelsior with dry cement; and still another tumbles dry excelsior with a thin slurry of the cement in water. In one way or another the excelsior and cement are combined and passed to the sheet-forming equipment.

The small-scale makers employ molding pans in which is spread by hand as evenly as possible the tangle of excelsior strands which have been previously coated with the inorganic binder. A plate of wood or steel is laid on the pan, the pans are piled one upon another, and pressure is applied until the plates rest on the pan edges or against stops. The pile is then clamped and the stack set to one side until the cement has hardened enough to maintain the compressed size of the mat. When the cement has hardened sufficiently, the boards are removed from the pans, dried, and trimmed. Drying may be postponed until after a hardening period is allowed for the cement. The pans are cleaned and returned to the process. A variation of this process is one in which a tall stack of pans is formed, the weight of the pile being more than ample to supply the necessary compression. Newly filled pans are introduced to the bottom of the pile and hardened sheets taken from the top of the pile. The pile height is often 20–40 ft. depending upon the pressure and time required for the cement to harden.

In large-scale operations the cement-coated strands of wood are mechanically deposited more or less uniformly on a moving steel or rubber belt. A top moving belt supplies the compression, and the whole moves forward until the cement has hardened enough to hold the compressed thickness. Fast-hardening cements such as calcined gypsum or magnesium oxysulfate are especially useful in this process as better speeds can be maintained with shorter belts. Heat is sometimes applied to the compressed mat to hurry the hardening of the binder. The Herkalith Company in Germany belt-forms the mat using magnesium oxysulfate as the binder. The belts holding the mat in compression pass through a heated tunnel where the binder hardens. The hardened sheet is cut to length and is passed to a dryer. Emerging from the dryer

the sheet is cooled, trimmed, and placed in stock. Thus the process is truly continuous. In a variation of the high-stack method the stack of molds is enclosed, and heated air or steam passed upward through the chimney surrounding the stack of molds to accelerate cement hardening.

The shorter wood fiber strands do not change the excelsior methods materially. Compression forces are reduced and hold-down times shortened, but otherwise the processes are similar. The fine wood fiber boards such as the Belgium Emsen board require an entirely different process, the only similarity being the ingredients of the board, wood, and inorganic binder. This process consists of dry-mixing the cement, wood, and asbestos fiber; then adding water in excess to form a thin slurry. The slurry is run to one or more vats, in which turn wire-faced wheels. The hydrostatic head acting on the wheels forces stock against the wire. Most of the water passes through the wire into the interior leaving the stock on the wheel. Pumps remove the water from the wheels maintaining the hydraulic differential inside and out. A felt picks up the stock deposited on the wire of the wheels and transports it to a large accumulator roll where the stock is again transferred, this time from the felt to the accumulator roll. By depositing the stock through a number of revolutions of the accumulator roll, a variety of thicknesses can be made. The sheet is then stripped from the accumulator roll and piled with plates and flat wires for repressing.

Uses. The excelsior type wood–inorganic binder board is the only one produced extensively in the U.S. The major present use is for roof decks under built-up roofing. For this purpose thicknesses of 1½–3 in. are common. Thinner boards will serve as form boards in casting concrete or other light weight inorganic roof slabs. Exterior sheathing under stucco is another application for the thinner boards and as a plaster base for interior plastering. Stucco or plaster base boards require a metal mesh over all joints to prevent cracking. The thinner sheets are also suitable for rough flooring because of good nail holding and spanning strength. A rough floor having a leveling coat of ½ in. of cement makes a good base for floor tile application. In waterproof binder types the board is suitable for roof boarding under shingles.

The unusual properties of the excelsior boards are their resistance to fire and rot, and their acoustical absorption. These properties combined with comparatively good strength and workability indicate the many uses to which the wood – inorganic binder wallboard can be put.

ASBESTOS-CEMENT BOARD

Asbestos-cement wallboards are unique among the wallboards generally available in being completely inorganic and highly weather resistant without any surface treatment. They are therefore entirely incombustible and are not damaged by water. They are made in ⅛–½ in. thicknesses and in size 4 by 8 ft. and smaller, and are usually a light gray color natural to portland cement but can also be obtained with integral and surface colors.

The physical properties that established asbestos-cement boards as wallboards are hardness, toughness, bending strength, workability, and fire and water resistance. Toughness and bending strength allow use of thin boards, making a comparative light workable wallboard of normally heavy unworkable materials, while the other properties contribute to serviceability.

The most popular asbestos-cement wallboard for residential use is ⅛ in. thick and 4 by 4 ft. or 4 by 8 ft. This board is used for wainscoting and wall application, door

veneer, cabinets, and other such uses. The thicker sheets are prefabricated for office partitions and wall structures of other types. They are also used in marine walls for fire safety.

See *Asbestos-cement products.*

Bibliography for Other Wallboards

INSULATING BOARD

(1) *America's Demand for Wood 1920–1975*, Stanford Research Institute, 1954.
(2) Commercial Standard CS 42–49, Structural Fiber Insulating Board, U.S. Dept. of Commerce.
(3) Eberhardt, L., *The Bauer Story on Hardboard and Insulating Board*, Bauer Brothers Co., Springfield, Ohio, 1954.
(4) Federal Specifications LLL-F-321b. Fiberboard: Insulating (1942).
(5) Heritage, C. C., and Duval, T. C., *Forest Products Research Soc. Ann. Proc.*, **1**, 7 (1947).
(6) "Insulation Board, Wallboard, and Hardboard," *U.S. Forest Products Lab. Rept.*, **1677** (1950).
(7) "International Fiberboard Process," *Pulp & Paper Mag. Can.*, **50**, No. 5, 78 (1949).
(8) Jessen, H. C., "Drying of Insulating Board," *Tappi*, **35**, 455 (1952).
(9) Lathrop, E. C., and Naffziger, T. R., *Tech. Assoc. Papers*, **31**, 337 (1948).
(10) Lowgren, U., *Forest Products Research Soc., Ann. Proc.*, **2**, 83 (1948).
(11) Luxford, R. F., *U.S. Forest Products Lab. Rept.*, **1151** (1953).
(12) "Methods of Test for Evaluating the Properties of Building Boards," *U.S. Forest Products Lab. Rept.*, **R1712** (1948).
(13) Perot, J. J., *Tappi*, **36**, 69 (1953).
(14) "Quick New Interiors with Insulating Board," *American Builder*, **72**, No. 11, 90 (1950).
(15) Stamm, A. J., and Harris, E. E., *Chemical Processing of Wood*, Chemical Publishing Company, N.Y., 1953, p. 350.
(16) Stephenson, J. N., ed., "Manufacture and Testing of Paper and Board," *Pulp and Paper Manufacture*, McGraw-Hill, N.Y., 1953, Vol. III, p. 517.
(17) Sweeney, O. R., and Arnold, L. K., *Engineering Exptl. Sta. Iowa State College Bull.*, **136** (1937).
(18) Texor, C. K., *Forest Products Research Soc. Ann. Proc.*, **2**, 89 (1948).
(19) Turner, H. D., Hohf, J. P., and Schwartz, S. L., *Forest Products Research Soc. Ann. Proc.*, **2**, 100 (1948).
(20) Varossieau, W. W., *Forest Products Research and Industries in the United States*, Meulehoff, Amsterdam, 1954, p. 482.
(21) Vazquez, E. A., *Internatl. Sugar J.*, **51**, No. 5, 149 (1949).
(22) "Wallboard Production and Uses," *Northeastern Wood Utilization Council Bull.*, **31**, 79 (1950).
(23) Walton, C. L., *Paper Trade J.*, **134**, 30 (1952).
(24) Weber, G. G., *Ind. Eng. Chem.*, **27**, 896 (1935).
(25) Weber, G. G., *U.S. Natl. Bur. Standards Rept.*, BMS **13** (1939).
(26) Whittemore, H. L., and Stang, A. H., *U.S. Natl. Bur. Standards Rept.*, BMS **31** (1939).

GYPSUM BOARD

(27) "Board Products," *Am. Lumberman Building Products Merchandiser*, 281 (April 9, 1949).
(28) "Board Products, Wall Tiles," *Am. Lumberman Building Products Merchandiser*, 317 (April 8, 1950).
(29) Lenhart, W. B., *Rock Products*, **51**, No. 3, 84 (1948).
(30) Lenhart, W. B., *Rock Products*, **52**, No. 2, 91 (1949).
(31) Lenhart, W. B., *Rock Products*, **55**, No. 1, 152 (1952).
(32) Mitchell, N. D., and Regan, J. V., *Building Materials and Structures Rept.*, **135** (U.S. Dept. Commerce) (1953).
(33) Nordberg, B., *Rock Products*, **53**, No. 12, 83 (1950).
(34) Stangland, R. S., *Rock Products*, **44**, 32 (1941).
(35) *Survey of Current Business, U.S. Dept. Commerce*, **34**, No. 2 (1954).
(36) "Take Wallboard Plant to Quarry," *Rock Products*, **46**, 50 (1943).
(37) "The Technology of the Manufacture of Gypsum Products," Department of Commerce, Bureau of Standards No. 281 (1926).

(38) "U.S. Gypsum's 50 Years of Progress," *Rock Products*, **55**, No. 2, 94 (1952).
(39) Utley, H. F., *Pit and Quarry*, **45**, No. 1, 82 (1953).

WOOD–INORGANIC BINDER BOARD

(40) Bender, F., *Paper Trade J.*, **130**, No. 19, 26 (1950).
(41) Dale, J. D., "Durisol Light Weight Pre-Cast Concrete, Wallboard Production and Uses," *Northeastern Wood Utilization Council Bull.* No. **31**, 79 (1950).
(42) Elmendorf, A. E., *Paper Trade J.*, **130**, No. 6, 29 (1950).
(43) Elmendorf, A. E., *Forest Products Research Soc.*, **4**, No. 2, 87 (1954).
(44) Elmendorf, A. E., *Proc. Forest Products Research Soc.*, **5**, 155 (1951).
(45) "Processed Wood Products," *Architectural Forum*, **67**, No. 3, 223 (1937).
(46) Risi, J., *Pulp & Paper Mag. Can.*, **52**, 82 (Jan. 1951).
(47) Stamm, A. J., and Harris, E. E., *Chemical Processing of Wood*, Chemical Pub. Co., N.Y., 1953, p. 285.
(48) Varossieau, W. W., *Forest Products Research and Industries in the United States*, J. M. Meulenhoff, Amsterdam, 1954, p. 496.

E. M. JENKINS

WALNUT (ENGLISH) OIL. See *Fats and fatty oils*, Vol. **6**, pp. 144, 147.

WARFARIN. See *Poisons, economic*, Vol. **10**, p. 873.

WAR GASES. See *Gas warfare agents.*

WASTES, INDUSTRIAL

The term industrial waste is generally understood to refer specifically to the liquid waste produced as a result of some industrial operation, as distinct from an industry's solid refuse or its gases, fumes, and vapors. Like municipal sanitary sewage, most of such liquids must ultimately be disposed of into rivers or other water courses. The liquid wastes of a community, whether domestic sewage or industrial wastes, should receive appropriate treatment before discharge into streams in order to prevent gross pollution. The treatment methods for domestic sewage are based on a fundamental and growing body of knowledge. These methods, however, are not suitable for all industrial wastes, which are quite varied in character. Frequently a new industrial process development will produce a waste that is not amenable to treatment by any of the conventional methods. For such wastes, laboratory investigations followed by pilot-plant studies must precede final design of treatment works. See also *Sewage*; *Smokes and fumes.*

According to a 1948 survey, 70 million persons in the U.S. live in communities served by sewerage systems, and the number of persons so served increases more rapidly than the national population. In the same year, the population equivalent of the nation's industrial wastes, on the basis of organic strength of the waste, was estimated to be 55–60 million people. This comparison does not fully express the magnitude of the industrial wastes problem. Many constituents of industrial wastes, without counterpart in domestic sewage, are not represented by the "population equivalent." Yet many of these constituents are responsible for the most detrimental effects of industrial wastes. The volumes of process water per unit of manufactured product are generally well known. Except for some rinse and cooling waters that may safely be discharged into storm sewers, most process waters end up as a waste requiring specialized treat-

ment and disposal methods. The volume of a waste, together with its composition and concentration, is the measure of each particular problem (see Table I).

Broadly stated, pollution of streams with industrial wastes degrades the physical, chemical, and biological qualities of the receiving waters. This degradation gives rise to a variety of economic problems that are the concern of all communities and industries downstream from the point of pollution. The most apparent of these problems is the damage to the quality of the stream and its fitness for subsequent domestic and industrial use. Depending on the character of the pollutional material, this damage may take the form of increased concentrations of hardness and encrustants, increased color and turbidity, increased corrosiveness, increased concentration of taste- and odor-producing substances, and dangerously high concentration of toxic substances. In extreme pollution such as in the Merrimac and Raritan rivers, the pollutional load in some sections has risen to levels that will not permit the use of the water for municipal or industrial purposes. In less extreme instances of pollution, existing water purification plants are unable to remove enough of the increasing pollutional load to produce satisfactory water. This has been notably true with respect to taste- and odor-producing substances.

The second type of problem resulting from industrial pollution is the changes produced in the biological balance of the receiving stream. These may come about because of siltation and the laying-down of sludge blankets over spawning beds; they may result from a marked shift in the pH of the water; they may be due to a lowering of the dissolved oxygen content of the stream; or they may be due to cumulative toxic effects of certain pollutants. In extreme cases, such changes drive out or kill off the normal biological fauna and exhaust the capacity of the stream for self-purification. In these latter cases, the effects of the industrial pollution will be felt far downstream from the point of pollution; they may extend down to tidewater and destroy a thriving shellfish industry. It is this aspect of pollution problems that receives the attention of the fish and wildlife interests.

Such changes also cause a loss of recreational assets of downstream communities. In increasingly populous and industrialized areas, boating, swimming, camping, and the like become rarer pleasures, and natural facilities for such outdoor sports take on increasing importance in the conservation movement.

Loss of property values results downstream from points of severe pollution. Under common law and the "reasonable use" rule, riparian owners are entitled to recover damages for such losses. Beyond the individual owner, however, there is the cumulative loss to the community of declining property values.

Finally, the relationship between an industry's waste and the receiving stream and the costs of the intervening treatment required have a marked effect on industrial operations. It is one of the factors that enters into site selection for new plants or the enlargement of existing plant facilities and capacity. Ultimately the cost of industrial waste treatment is a part of the cost of production. When waste treatment costs mount to the point that they represent a sizable fraction of production costs, the resultant product may be in a poor competitive position.

Classification of Industrial Wastes

Industrial wastes can be classified according to the biological, chemical, and physical properties that may contribute to degradation of receiving waters. Although

TABLE I. Industrial Wastes.

Industry	Waste	Production unit	Flow, gal./unit	BOD, p.p.m.	BOD, lb./unit	Suspended solids, p.p.m.	Suspended solids, lb./unit	Other possible constituents
Alcohol distillery	Cooking and fermenting	Bushel of grain	290	26	0.06	—	—	
	Distilling	" " "	3.1	360	0.01	—	—	
	Feed recovery plant	" " "	385	1,300	0.43	—	—	
	Total	" " "	700	95	0.60	—	—	
Antibiotic	Penicillin spent broth	—	—	4,000	—	1,200	—	
	Penicillin spoiled batch	—	—	25,000	—	—	—	
	Streptomycin spent broth	—	—	2,500	—	—	—	
Beet sugar	Flume water	Ton of beets	2,200	200	3.7	800	15	
	Process water	" " "	660	1,200	6.8	1,100	6.1	
	Lime drainage	" " "	75	1,400	0.7	450	0.3	
	Steffens	" " "	120	10,000	10	700	0.7	
Brewery	Total	Barrel of beer	320	1,200	3.1	450	1.2	
Cannery	Beans, green	Case #2 cans	42	400	0.14	75	0.025	
	Beets	" " "	25	2,500	0.5	1,100	0.23	
	Corn	" " "	25	3,000	0.63	980	0.2	
	Peas	" " "	25	2,400	0.5	2,800	0.58	
	Tomato, whole	" " "	15	570	0.07	190	0.02	
	Tomato and puree	" " "	7.5	2,900	0.18	950	0.06	
	Apricots	" " "	55	380	0.2	260	0.12	
	Citrus fruit, sections	" " "	50	1,900	0.8	270	0.03	
	Citrus fruit, juice	" " "	50	340	0.14	170	0.07	
	Pears	" " "	50	450	0.19	310	0.12	
Coal (anthracite)	Washery	Ton of coal	—	—	—	—	260	
Coal (bituminous)	Mine drainage	Day per acre mined area	1,000	—	—	—	—	Sulfuric acid, iron, sulfide, hardness
Coke and gas	Ammonia still	Ton of coal	20	4,000	0.7	300	0.05	Phenolic compounds
	Benzene recovery	" " "	15	650	0.08	130	0.02	Phenolic compounds, cyanides, tars, oil

Dairy	Receiving and bottling	1,000 lb. milk	—	—	18	—	11	
	Ice cream plant	" " "	—	—	10	—	6	
	Skim milk drying	" " "	—	—	4	—	2.4	
	Milk evaporation	" " "	—	—	6	—	3.5	
	American cheese	" " "	—	—	16	—	8	
Meat packing	Cattle process	Ton live wt.	3,200	1,050	28	950	25	Grease, high nitrogen
	Hog process	" " "	4,300	860	31	580	21	Grease, high nitrogen
Paper industry	Rag and deinked pulp	Ton of product	55,000	150	70	720	330	
	Kraft pulp	" " "	63,000	130	69	150	80	
	Sulfite pulp	" " "	48,000	1,250	500	110	43	Color, sulfite
	Groundwood pulp	" " "	3,000	2,400	5.9	6,000	15	
	Book paper	" " "	13,000	55	6	460	50	
	Bond paper	" " "	2,000	7,800	13	36,000	60	
	Tissue paper	" " "	25,000	40	8.3	190	40	
	Wrapping paper	" " "	27,000	44	10	190	43	
	Board		5,600	64	3	260	12	
Petroleum	Total	Barrel of oil	110	110	0.1	200	0.18	Oil, phenols, acid, alkali, reduced sulfur compounds
Plating	—	—	—	—	—	—	—	Acid, alkali, heavy metals, cyanide
Steel industry	Pickle liquor	—	—	—	—	—	—	5% H_2SO_4+15% $FeSO_4$
Tannery	Total	100 lb. hide	800	1,200	7.8	2000	13	Alkali, chromium
Textile industry	Cotton kiering and rinse	100 lb. of goods	116	1,650	1.6	70	0.07	Alkali
	Silk degumming		850	990	7.0	520	3.7	Iron, lead, aluminum
	Cotton desizing		110	1,740	1.6	55	0.05	
	Cotton bleaching		115	240	0.3	40	0.04	
	Cotton souring		336	70	0.2	40	0.11	
	Cotton direct dyeing		640	220	1.2	15	0.08	Color, acid, alkali
	Cotton sulfur dyeing		540	1,330	6.0	15	0.07	Alkali, color, sulfides
	Cotton vat dyeing		1,900	140	2.2	15	0.24	Alkali, color

it is not always possible to translate properties of waste into terms of effects on receiving waters, for purposes of classification the properties are treated as if the pollution potential of a waste is either directly proportional to the intensity of its components or represented by a designated standard test. The numerous properties possessed by some industrial wastes may require their inclusion in several classes.

Biological Properties. *Biologically Oxidizable Material.* Discharges containing material that can be oxidized when utilized as substrate by bacterial flora are classified as biologically oxidizable. Dissolved oxygen present in natural waters serves as the source of oxygen for this process. The vast majority of industrial wastes are classed within this group.

Wastes that may undergo biochemical oxidation are sometimes termed "organic" wastes, since many organic compounds are readily oxidized through biochemical action. In this definition the term "organic" is inexact because organic compounds differ widely in their susceptibility to biological decomposition and some inorganic substances, such as ammonia, are subject to biochemical oxidation. The pollutional potential of these wastes containing significant amounts of biologically oxidizable materials is usually evaluated from a standard 5-day biochemical oxygen demand (BOD) determination. Examples of wastes in the organic pollution group are those from dairies, distilleries, pharmaceutical houses, canneries, and pulp and paper industries.

Pathogenic and Indicator Organisms. Discharges which may contain pathogens or saprophytes commonly employed as indicators of contamination—such as organisms of the coliform group—are included in this category (see *Water (municipal)*). Wastes from slaughterhouses and tanneries are examples of wastes that might be classed within this group.

Chemical Properties. *Toxic Substances.* Discharges containing substances that interfere directly, or through synergistic action, with the native aquatic population of receiving waters may be classed as toxic wastes. Exhaustive studies are required to evaluate toxicity in quantitative terms. Many of the existing standards pertaining to toxicity are of an empirical nature. Examples of toxic substances present in some industrial wastes are acids, alkalies, cyanides, salts of heavy metals, sulfides, fluorides, and phenolic compounds. Toxicity is frequently associated with wastes from metal finishing industries, coke and gas plants, petroleum refineries, and tanneries.

Salinity and Hardness. Discharges containing relatively high concentrations of salinity and/or hardness can impair the quality of lower riparian potable water supplies. Examples of wastes that may fall within this classification are oil field brines, acids, alkalies, mine drainage, and brine from ion-exchange units.

Acid wastes, such as those from steel pickling and coal mining drainage that contain only inorganic compounds and no toxic metals, may have serious effects on the biota of a stream because of the lowering of the pH. By reducing or stopping the natural self-purification processes in a stream, these wastes retard the biological stabilization of accompanying organic wastes, and the pollution effects are extended farther downstream.

Physical Properties. *Temperature.* Discharges that alter the temperature of receiving waters to an extent sufficient to interfere with the native aquatic population may be classed as temperature pollution. These wastes include condenser discharges and boiler blow-down.

Films and Scum. The presence of a separate phase floating on the surface of a

watercourse indicates film or scum pollution. Such conditions are frequently produced following discharge of wastes containing solvents, oils, or greases.

Turbidity. Discharges that increase the optical density of receiving waters by virtue of the presence of fine suspended material (usually colloidal) can be classified as turbidimetric pollution. Turbidity is determined from a measurement of optical density. Examples of this type of discharge are those from hydraulic mining operations, coal washeries, carbonization of coal, and petroleum refineries.

Suspended Solids. Discharges that contain undissolved solids, or that through interaction with constituents present in natural waters result in the formation of insoluble solids, can be classified as suspended solids pollution. Suspended solids are separated by filtration through a gooch crucible and determined gravimetrically. Examples of wastes containing suspended solids are those from coal washeries, pulp and paper mills, metal pickling processes, canneries, and wool scouring.

Color. Discharges that impair the natural color of receiving waters are classified as color pollutants. The character and intensity of color are evaluated from standard optical density determinations over the visual waveband of the spectrum. Examples of colored wastes are those from dyeing operations, canneries, and from chemical and explosive manufacture.

Taste and Odor. Discharges that impart taste or odor to receiving waters or that contribute to taste or odor in lower riparian potable water supplies are classified as taste and odor pollution. Substances such as phenolic compounds, solvents, petroleum products, and reduced sulfur compounds can impart taste and odor to water although present in minute concentrations.

A comparison of industrial wastes is presented in Table I. Industrial wastes vary from time to time and from plant to plant; hence, the values presented are intended to be indicative of the general expected order of magnitude.

Treatment Aims and Methods

Broadly stated, the plan for handling a particular waste aims at: (*1*) minimizing the total volume and concentration of waste produced, (*2*) recovery of potentially valuable fractions of the wastes for re-use or by-product development, and (*3*) most economical treatment of the remainder, consonant with water resource conservation.

The methods employed fall into the following categories.

Reduction of Volume of Wastes. A careful analysis of the points in an industrial process at which water is used will frequently reveal economies that can be effected without sacrifice of product quality. The elimination of leaks in water piping or unnecessary use of water, more efficient use of water through countercurrent washing tanks, and re-use of batch solutions that can be made up to required strength are typical of methods that reduce the cost of water employed in a process and simultaneously reduce the cost of treatment of the resultant waste. Cooling and condensate waters should also be segregated from process waters for separate discharge if they are of sufficiently good quality to justify such discharge, and their quantity is great enough to justify the added cost of separate collection.

Waste Recovery. In some industries, certain fractions of the wastes have been found to contain materials that can be recovered. Calcining of lime sludges, recovery of caustic soda from wastes from the kiering of cotton cloth, and recovery of oil from wastes are examples. Usually the cost of recovery is somewhat more than the cost of

equivalent fresh material but the concomitant reduction in cost of waste treatment justifies such recovery processes.

By-product Recovery. Materials recovered from a waste are frequently not good enough in quality for re-use but may be recovered economically for by-products, as illustrated by segregation of skim milk, buttermilk, and whey from milk industry wastes, the conversion of blood and paunch contents from slaughter houses into fertilizer, and the production of animal feed from brewery and distillery wastes. Again, although the value of the by-product alone may not justify the cost of recovery, the reduction in cost of waste treatment needs to be taken into account.

Segregation of Waste. In a large industrial plant there may be several classes of waste varying in volume, strength, and toxicity. One may be readily amenable to biological treatment with domestic sewage, another may be quite inimical to such processes, and another may have value for by-product recovery. Careful study of their characteristics may indicate that each waste should be handled and treated separately. Thus at a plant making woolen blankets, the wool scouring waste may be processed by acid-cracking or centrifugation to yield wool grease before allowing it to become mixed with waste dye batches. It is especially necessary that any toxic wastes be segregated. All such segregation requires careful planning of separate plant sewer systems.

Neutralization. In many industrial processes operating on a batch basis, the production of wastes is not uniform in time but is necessarily discharged to the plant sewers periodically in "slugs." Where some batches are acid and others are alkaline, or where some contain reducing agents and others oxidants, a beneficial self-neutralization may be effected if the wastes are pooled over a 24 hour or preferably longer period. This requires the provision of a detention basin of capacity equal to the volume of waste produced during the pooling period. Because thermal or density stratification may limit thorough mixing and neutralization, some form of mechanical mixing increases the effectiveness of the basin. Diffused air aeration is excellent for this purpose since it generates turbulent mixing, prevents sedimentation of suspended solids, and supplies dissolved oxygen to wastes that would otherwise become septic during the detention period. In addition to neutralization, detention and mixing over an adequate period produce a waste of relatively uniform composition.

Equalization of Flow. Detention tanks also provide the means of regulating the flow of wastes to the treatment works. Biological treatment works operate at much higher efficiencies when the rate of flow and the composition of the waste are constant. Where mixed industrial wastes are released from detention tanks to municipal sewers for dilution and treatment with domestic sewage, it is often desirable that the release rate be proportional to the flow of domestic sewage. Thereby uniformity of dilution of the waste in the sewage is achieved and more efficient treatment can be effected.

Complete Treatment. Industrial plants so located as to be inaccessible to municipal sewers should provide suitable treatment of their waste before release to a receiving stream. Moreover, municipal sewer ordinances may regulate the type of wastes that are admissible into the sanitary sewer system and may exclude those that are inimical to combined treatment with domestic sewage. Industrial plants producing wastes that are thus excluded may be required to provide suitable treatment before release to a receiving stream.

Partial Treatment. Short of absolute exclusion of certain industrial wastes from municipal sewers, local ordinances may require that industries provide partial treat-

ment of wastes so that the resultant treated effluent can be handled in combination with domestic sewage.

Treatment with Domestic Sewage. Many industrial wastes can be more effectively treated in combination with domestic sewage than alone. This is the case where the industrial waste lacks nutrients such as carbon, nitrogen, and/or phosphorus essential for bacterial nutrition. Domestic sewage, because of its heterogeneous composition, will provide these essentials, provided the ratio of industrial waste to domestic sewage is not excessively high.

The following discussion of specific treatment methods reviews more specifically the range of these methods with illustrations of typical wastes with which they have proven effective.

Treatment Techniques

TREATMENT WITH DOMESTIC SEWAGE

No In-plant Pretreatment. The discharge of industrial wastes into municipal sewers in most instances is the most satisfactory method of disposal, particularly where the wastes require treatment before they can be discharged into a stream. However, unless satisfactory financial arrangements can be made and the industrial wastes received in a manner in which the treatment plant can handle them, those responsible for the operation of a municipal disposal system cannot be expected to subscribe to the general statement made above. The minimum pretreatment required is that necessary to render the waste harmless to the sewerage system, the plant operation, and the receiving stream. This minimum pretreatment should include: (*1*) removal of materials that will clog the sewers, either by sedimentation or deposition on the sides, such as grit, sand, pulps, greases, and tars; (*2*) removal of materials such as acids and abrasives, that may damage the sewage collection and treatment structures; (*3*) removal of hazardous wastes, including volatile, flammable or toxic materials; (*4*) removal of toxic materials that will appear in large enough concentrations to affect the sewage treatment process or the receiving stream; and (*5*) removal of materials that will exceed the treatment capacity of the sewage plant and impair its efficiency or pre-empt its capacity in an inequitable manner.

In addition to these minimum conceivable pretreatment requirements, additional treatment may be needed to meet the standards of waste quality set by the municipality.

Pretreatment can often be made unnecessary or be kept to a minimum if certain in-plant precautions are taken to minimize the effect on the sewerage system or treatment plant. Many precautions apply not only to discharges into sewerage systems but also to any industrial waste problem. These include: (*1*) equalization of waste load preferably measured by the weight of BOD or suspended solids discharged per unit of time; (*2*) equalization of flow compatible with equalization of load; (*3*) storage and mixing as necessary to equalize loads, to permit interaction of wastes (such as acids and alkalies, oxidants and reductants), and to effect dilution of highly toxic materials (such as cyanides, aniline, and phenols); (*4*) separation of special highly concentrated or toxic wastes for disposal by means other than discharge to sewers or for individual pretreatment; (*5*) reduction of waste load by improved product handling, better in-plant housekeeping, and special employee training for waste control and reduction; and (*6*) reduction of waste load by process changes and manufacturing techniques specially designed for waste control.

Equalization of waste load, particularly with biological sewage treatment methods, is one of the most important requirements if pretreatment is to be avoided. The amount of equalization necessary will depend upon the relative sizes of the industrial waste load and the total load received at the treatment plant. For example, a large dairy (300,000 lb. of milk per day) in a very large municipality (1 million population) should be able to discharge its wastes, including the whey, intermittently without adversely affecting the sewage treatment plant because of the large dilution ratio and the long travel time of the sewage. On the other hand, a small dairy (20,000 lb. of milk per day) in a small city (10,000 population) would probably be required to equalize the discharge carefully and might be prevented from dumping the whey. Although equalization of waste load over the entire 24 hours is considered desirable, sometimes controlled discharge during the off-peak hours at night can be advantageously used. Such practice is generally limited to small or medium-sized systems where flow periods are relatively short and the industry is relatively large. Although these special equalization methods require good cooperation between the industry and the municipality, and careful control, their mutual advantages to both the industry and municipality are obvious.

With In-plant Pretreatment. If an industrial waste cannot be modified enough to meet the specifications set by the municipality short of using techniques of treatment which were previously discussed, then pretreatment of the waste is necessary. The amount of pretreatment desirable is usually only enough to permit the waste to be discharged. Even when special charges are made for handling industrial wastes, it is generally unlikely that the industry can treat the waste at less cost than the municipality. Thus it is not economical to provide more pretreatment than is actually required, except under very unusual circumstances.

Pretreatment can be divided into three general categories, physical, chemical, and biological.

Physical pretreatment is generally limited to fine screening, settling, and skimming, and is used mainly to remove materials that would clog sewers, impair operation of treatment plant units or machinery, or be a hazard because of their volatility.

Screening is most successfully applied to the removal of organic solids such as those occurring in canning and papermaking operations.

In canning practice, 40–50-mesh vibrating screens have gained wide acceptance, while for fibrous solids, such as those in paper wastes, rotary screens of 60–80 mesh with liquid flow from the outside of the screen to the inside are considered superior. Fine screens should provide for continuous mechanical removal of the screened solids, be self-cleaning as far as possible, should require a minimum amount of supervision, and be rugged enough to run continuously without excessive maintenance. Screens that do not have these qualities can only be considered as makeshift or temporary expedients and will not perform satisfactorily.

Settling (Pretreatment). Sedimentation is most frequently used for removal of heavy solids such as grit which will settle out in sewers. Elaborate mechanically cleaned grit chambers may be employed where the amount and character of the material warrant their use. Many industrial waste grit chambers are merely tanks or pits that act as combined mixing, equalization, and grit-removal devices. Periodic cleaning is required, but their use is often satisfactory for removal of moderate quantities of grit from industrial wastes that do not have settleable organic solids. Mechanically cleaned sedimentation chambers for the removal of settleable solids are

rarely used ahead of municipal sewers, because the removal of such material is not generally required, nor is it economical to do so. Certain situations may dictate pretreatment by sedimentation for removal of settleable solids, such as recovery of valuable materials, removal of precipitated toxic metals, and protection of an overloaded sewage treatment plant.

Sedimentation is often practiced in conjunction with lagooning prior to discharge into sewers. In such instances the settled solids are usually an unwanted by-product of lagooning, which is generally used for flow and load equalization, mixing and chemical interaction. Lagoons are effective for such purposes, but their practicability is often influenced by sedimentation and sludge removal problems.

Skimming or flotation is often referred to as "reverse sedimentation." Where oils, greases, or other floatable materials that should be excluded from sewers are to be removed by pretreatment, a tank, lagoon, or special flotation device is required. Where the floatable materials are not excessive, a single baffled outlet on a sedimentation tank or lagoon is all that is required. Skimming can be by hand or semiautomatic through some type of surface draw-off device. Where floatable materials must be continuously removed in significant quantities, mechanically skimmed sedimentation tanks, oil separators, or special flotation tanks should be used. Although skimming devices are often simple to construct, special attention should be given to their use because of the hazards involved, principally from fire. Since oil or other flammable products are usually involved, fire problems must be considered. Although enclosed skimming devices reduce the fire hazard, they are more difficult to clean and maintain and are likely to be left unattended and forgotten. Unless enclosed units have an easily operated and controlled skimming arrangement and proper facilities for easy inspection, they cannot be counted upon to perform satisfactorily.

Chemical pretreatment before discharge into sewers covers a wide range of problems, but most of these fall into three general categories: neutralization of acids or alkalies, removal of oxidants and reductants (principally reductants), and removal or change of toxic constituents (for example, cyanides and heavy metals).

Where chemical pretreatment is required, flow equalization and waste mixing are often advantageous and in many instances necessary. Sometimes this is all that is required because sufficient chemicals occur in the total waste to effect the necessary neutralizations or other desirable reactions. When further treatment is required, prior equalization simplifies the control of the treatment process and saves chemicals.

Usually neutralization of acid is the problem, and since lime and limestone products are the cheapest virgin alkaline materials, they are most often used for this purpose. Since sulfuric acid is the most prevalent waste acid, neutralization problems arise when lime is used for neutralization because of the relative insolubility of calcium sulfate. Calcium sulfate scaling problems can be reduced by the use of dolomitic lime and by control of the sulfuric acid concentration of the waste. Crystal seeding with gypsum crystals or previously precipitated calcium sulfate also has been shown to control scaling and reduce the volume of sludge produced. Upflow limestone beds provide a simple economical means for the neutralization of waste acids. With sulfuric acid their use is limited to dilute acid ranges because of calcium sulfate precipitation on the limestone particles, which inactivates the bed. Sulfuric acid concentrations of over 2,000 p.p.m. may cause difficulties, and 5000 p.p.m. is about the upper limit for upflow beds. Excess sulfate or calcium ions in the acid waste will reduce these limits because these ions will reduce the solubility of the resulting sulfate

Alkalies offer fewer problems for disposal into sanitary sewers because they do not attack sewer structures, and often all that is required is simple equalization of discharge. Where neutralization is required, sulfuric acid is usually employed because of its low cost. Waste flue gas has also been used in special instances, but the low cost of the neutralizing agent (carbon dioxide) is partially offset by high installation costs.

Oxidizing and reducing agents in industrial wastes can cause problems when discharged into sewers. Since sewage itself contains many reduced compounds, oxidizing agents are not generally as troublesome as reducing agents. Usually equalization of flow and load, or storage and mixing with reducing substances discharged in the waste, will solve most problems. When such measures fail, segregation and separate disposal, or treatment with some reducing substance such as sulfite, bisulfite, or even sulfide may be necessary. Unless the oxidizing substance interferes with the sewage treatment process, there is no reason for reducing it by pretreatment. Since one of the chief aims of sewage treatment is to raise the oxidation level, an oxidant may be a help to the process if it does not appear in such high concentrations as to be dangerous or biologically toxic.

Reducing agents on the other hand are quite troublesome when discharged into sewers, even though they are not generally considered toxic to biological life. Reduced compounds add to the oxidation requirements of the treatment process, lead to conditions that give rise to odors and other nuisances both in sewers and at the treatment plant, and make disinfection by chlorine difficult and expensive.

Reductants can be pretreated in much the same manner as oxidants except that any chemical treatment must be used in a reversed manner. Reduced sulfur compounds both inorganic and organic are most frequently encountered. Because so much oxidation is required to treat sulfides adequately either chemically or biochemically, these compounds are often removed by acidification followed by scrubbing with caustic solutions.

Oxidation by chlorine or some other chemical oxidizing agent is frequently used. The speed and simplicity of operation and the completeness of oxidation makes chlorine a good treatment for wastes containing reduced compounds. The cost of chlorine is often an important factor, and it may offset the advantages. This is particularly true for highly reducing compounds such as sulfides which use almost 9 p.p.m. of chlorine for each p.p.m. of sulfide oxidized to sulfate.

Simple aeration is also frequently effective for removal since both oxidation and scrubbing actions are involved. One disadvantage in many treatment operations for removal of reduced substances is that a water pollution problem becomes an air pollution problem.

Biological Pretreatment. Toxic substances can be troublesome when received at sewage plants because many systems rely on biological methods for their treatment. Even though no biological problems are involved at the plant, the receiving streams may be affected by the discharge of toxic substances. Again, equalization of flow and toxic load or segregation and separate disposal of major offending wastes may be all that is required to solve toxicity problems. Pretreatment methods are similar to those used in regular industrial waste treatment practice (see p. 906).

Chemical and biological pretreatment to reduce the solids and BOD load discharged to sewage systems follows much the same pattern and methods as full industrial waste treatment, except that the treatment need not be as complete and the

resulting sludges do not have to be separated but can be discharged with the total waste for subsequent removal at the sewage treatment plant.

Some toxic substances, such as copper, must be removed by precipitation, settling, and sludge removal before discharge into sewers. This is because of toxicity to sludge digestion processes at the sewage treatment plant. This requirement will not be necessary if biological methods are not used for sludge disposal.

SEPARATE TREATMENT

After all efforts to reduce waste flows and total waste loads have been made, it is then proper to consider the waste treatment problem remaining and its practical solution. Physical, chemical, and biological processes are available, but often combinations of these processes are required.

Physical methods include screening, settling, and flotation. Another physical process that often warrants consideration is controlled dilution by which wastes are stored in lagoons during periods of low stream flow and discharged to the stream during high flow when adequate dilution is available to prevent downstream nuisances. Although this method of waste disposal may seem crude, a properly designed waste disposal operation using controlled dilution is often the best and most practical solution.

Sedimentation. Plain sedimentation is used for removal of settleable material, and the methods and equipment employed are similar to those used for sewage treatment. Industrial waste practice uses more upflow and sludge-blanket-type sedimentation basins than sewage practice because these units are better adapted to the handling of wastes containing higher solids concentrations and producing more voluminous sludges than are ordinarily encountered in sewage disposal practice. Mining and papermaking are examples of industries in which sedimentation is a major portion of the waste treatment processes.

Chemical Treatment. The type of chemical treatment discussed here pertains to its use as a sedimentation aid for the coagulation of nonsettleable solids.

Alum and ferric iron salts such as ferric chloride, chlorinated copperas, and ferric sulfate are widely used as coagulants, particularly in the acid range pH 4.5–6.5. Iron salts are also effective in the alkaline range pH 8.5–10.5. Lime is usually employed in conjunction with the iron salts for alkaline coagulation. Ferrous iron is also an effective coagulant in this pH range, and lime and copperas are often used together. Although the ferrous ion is not considered as effective as the ferric ion, the cheapness of copperas (a waste product from steel pickling, and titanium ore processing operations) makes its use with lime an economical and effective coagulant. Lime alone is a good coagulant for many wastes, and although the effluent is not always as clear as that obtained with other agents, the low chemical cost and smaller resulting sludge volume produced warrants consideration for its use in many chemical treatment operations. Alum is not considered good with alkaline coagulation because of the large flocs produced and the fact that aluminum begins to go back into solution about pH 8.5. Sodium aluminate has been used successfully at these higher pH ranges. (Copperas is a name given to ferrous sulfate; chlorine is often added to the solution to oxidize the iron to the ferric state.)

With chemical treatment, it is important that pH control, chemical dosage, and flocculation time be given careful consideration if economical operation is to be realized. Many relatively small chemical treatment operations are more concerned with sim-

plicity of control and achieve good results and manpower savings by using excess coagulant at the expense of coagulant efficiency.

Lagoons are also effective sedimentation devices and have an important place in the industrial waste treatment field. Many of the objectionable features of lagoons, (see p. 905) can be overcome with careful planning. Important advantages of lagoons include their unusually large sludge holding capacity, their ability to handle large flow variations, their long settling period, and their low cost.

Flotation methods can be divided into two general categories, those that employ simple flotation and those that employ air bubbles to make solid materials floatable. Oil separators are typical examples of the first type. Often simple settling is also provided for in the separator with mechanical equipment to remove both settled and floated materials. Air flotation units are most widely used in the paper industry for waste treatment because of their early application to paper waste treatment and primarily because paper fibers are subject to rapid flotation. Flotation units are generally much smaller than sedimentation units for treating comparable flows. Detention times in flotation units are often 15 minutes or less, particularly with paper wastes. Air flotation is seldom used alone, a coagulant such as alum or lime usually being employed to form large enough aggregations of particles to permit their rapid flotation. Flotation units are best adapted to the separation of solids that are either light and fibrous, such as paper fibers and some cannery waste solids, or to greaselike materials that can be coalesced. Flotation of greaselike materials may be facilitated by entrainment in the surface film of finely diffused air bubbles.

The other type of chemical treatment is concerned with the use of chemicals to bring about a chemical change in the waste constituents either to permit their removal or to convert them into less objectionable forms. Some of the problems concerned with this type of treatment have been discussed (see p. 905). Because of the great variation in the chemical constituents of wastes, it is impossible to give many details concerning treatment. Certain treatment operations can best be handled on the concentrated wastes before dilution with wash waters, cooling waters, and general plant wastes. With these concentrated wastes, chemical treatment operations are often similar to plant processing operations and can best be designed and handled by plant chemists and chemical engineers who are familiar with such problems. Chemical operations on dilute mixed wastes are less familiar to plant chemists and the utilization of the services of experienced waste treatment consultants is often advisable.

Biological treatment is usually necessary in order to remove soluble and colloidal organic material from wastes. Aerobic biological methods employed for industrial wastes are the same in principle as those used in the treatment of sewage. These include biological lagoons, standard and high-rate or recirculating trickling filters, activated sludge, including both conventional and high-rate or high-load forms, and sand filters. Two anaerobic methods, anaerobic lagooning and waste digestion, used in industrial waste practice have no exact counterpart in sewage treatment practice.

With industrial wastes, aerobic processes often are more heavily loaded than their sewage treatment counterparts, particularly on the basis of pounds of BOD load per unit volume of treatment device. Part of this heavier load is due to the fact that industrial wastes are usually more concentrated than sewage, thus permitting greater treatment efficiency per unit volume. Because of higher concentrations and higher loadings, aerobic treatment units for industrial waste have more complicated oxygen transfer problems. Industrial waste practice utilizes mechanical diffusion of air, with

high-speed mixers, high-velocity air, or special devices to promote small bubble formation and the rapid solution of oxygen into the liquid. These special methods are necessary in order to maintain aerobic conditions in the heavily loaded oxidation units, but this is achieved at the expense of higher power requirements.

Anaerobic waste digestion is applicable to concentrated wastes as a means of stabilizing the organic content. Although the biological transformations are the same as those involved in sewage digestion the operation is different in principle. With waste digestion, the sludge remains in the digester as the carrying medium for the organisms that provide the desired biological transformations. The waste passes slowly through the sludge, usually by upflow, and is brought into intimate contact with the biologically active sludge. Digestion can remove up to 90–95% of the BOD at loadings that are higher than that possible with conventional aerobic treatment processes. The newer, more heavily loaded aerobic treatment units, particularly activated sludge type processes, have almost eliminated this advantage. Several disadvantages to waste digestion must be considered. The effluent from a digester often requires subsequent aerobic treatment even though it may have a relatively low BOD. Some of the products of digestion, particularly reduced sulfur compounds, create odor problems when the treated waste is finally exposed to the atmosphere. Also, the sulfides formed during digestion or originally present in the waste are toxic to the biological digestion process. Experience has shown that difficulties may be expected when the total sulfur content of the original waste is over 100 p.p.m.

Several problems encountered with the biological treatment of industrial wastes are not found with domestic sewage treatment. These include toxicity, nutrient deficiencies, and adaptability.

Toxicity may be overcome in many ways, the best of which is removal of the offending material. If this is not possible, its concentration may be kept within nontoxic limits by special dilution control. The biota can often be adapted to tolerate previously toxic concentrations of the offending material. This material is then biologically removed by such adapted organisms.

Nutritional deficiencies often occur with industrial wastes but never with domestic sewage. The requirements for nitrogen and phosphorus are well established, and these two elements appear to be the most important from a nutritional standpoint. At least when they are present biological activity takes place, and when they are deficient it is reduced. Nitrogen and phosphorus requirements have been established in relation to the BOD and the most commonly accepted ratio is 1 part phosphorus to 3 parts nitrogen to 60 parts BOD. Ratios as high as 1:3:100 have also been used with little effect on biological oxidation rates.

Most organic compounds are fortunately subject to biological decomposition but unfortunately not always in the concentrations encountered in industrial wastes. Also, the organism required for a particular decomposition must be naturally available in sufficient numbers to obtain the desired biological transformations. Sewage, soils, and even compost piles are good sources of aerobic biological seed organisms. On the other hand, digested sewage sludge and manure piles are the best sources for anaerobic biological flora.

Usually adaptation and development of a suitable biological population occur simultaneously. Both are accomplished by providing a proper biological environment for the treatment process and then subjecting the original biota to increasing concentrations of the waste, thus gradually developing a population flora adapted to the highest feasible concentration.

MISCELLANEOUS WASTE TREATMENT AND CONDITIONING METHODS

There are numerous methods of industrial waste processing which are used to eliminate or modify certain waste components in order to facilitate the final disposal of the waste. Such processes as ion-exchange, solvent extraction, evaporation, volatilization, degasification, and selective precipitation are often used to recover materials for re-use within the industry or for the production of a commercial product. Most of these processes are familiar to industrial chemists and engineers and their use in waste treatment practice is not unlike their industrial use.

SLUDGE DISPOSAL

The economical disposal of sludges from industrial waste treatment processes is often one of the most difficult problems encountered. This is also true of sludges from domestic sewage treatment plants, but their problems are often less complex. Sewage sludges are organic in nature and generally subject to biological stabilization by anaerobic digestion. By contrast, industrial waste sludges vary from about 100% organic to 100% inorganic material and often are not susceptible to digestion because they contain toxic substances or lack sufficient suitable organic material.

Relatively few industries produce waste organic sludges suitable for digestion, but the methods of treatment and final disposal for these sludges are similar to those used in sewage treatment practice. Typical examples in this category are wastes from the packinghouse, food processing, antibiotic, and fermentation industries.

Sludge conditioning, dewatering, drying, incineration, materials recovery, disposal, or dumping are all facets of sludge disposal. The combination of disposal techniques required in a particular situation will depend on many variables. Some of these variables include: (*1*) the drainability of the sludge and the preconditioning means by which it can be facilitated; (*2*) thickening and compaction characteristics; (*3*) organic content and susceptibility to decomposition; (*4*) value of the material recovered; (*5*) availability of suitable land for sludge lagoons, drying beds, and disposal dumps; (*6*) esthetic considerations; (*7*) continuous or intermittent sludge production; (*8*) economic considerations—initial investment vs. operating costs; (*9*) availability of suitable dumps or sewage disposal plant sites where joint disposal of municipal and industrial sludges can be effected; (*10*) development of uses for recovered or processed material; (*11*) air or stream pollution problems resulting from sludge disposal.

Digestion. For organic sludges susceptible to anaerobic digestion, the best method of disposal usually follows sewage treatment practice. See *Sewage*. The relatively small amount of organic sludge produced from a single industry seldom warrants the use of such complicated and costly techniques as vacuum filtration and incineration unless land space is at a premium. Open sand-bed drying is generally most applicable for digested sludges with final disposal for fill material or as a soil conditioner.

Filtration. Many industrial sludges are susceptible to dewatering by vacuum or pressure filtration. Chemical coagulation with iron, alum, or lime may be helpful and the use of diatomaceous earth filter aids is often found necessary to obtain satisfactory performance. Sludges that are largely inorganic often filter well without coagulants or filter aids.

Since pressure or vacuum filtration is widely used in industrial processes, the method of filtration used for a particular waste sludge problem is often dictated by the

experience with filtration within the industry or plant. Several of the factors above influence the choice of filtration equipment.

Lagooning. Lagoons may be used in a variety of ways for sludge disposal. Generally they effect the compaction, concentration, and storage of either digested organic sludges or inorganic sludges. Some lagoons may be used for dewatering and drying; subsurface drainage must be provided in such lagoons and they must periodically be taken out of service. The filled lagoon may be used for final disposal by leaving the sludge in place and possibly covering the surface with earth. Obviously construction of new lagoons is required as old ones are filled. The usual practice in sludge lagoon operation involves removal of the concentrated sludge by hydraulic dredges, draglines, or bulldozers for final disposal on land dumps or soil areas. Lagoons may also be used for digestion of organic sludges in addition to their other disposal functions. When so employed, the lagoon design may be influenced more by the requirements for proper digestion, and avoidance of odor nuisances, than by sludge concentration and disposal features.

Regulations and Standards

Authority is exercised over the discharge of wastes at four levels of government, namely federal, state, special interstate commissions, and metropolitan or municipal. The first three are concerned with the protection of natural waters while the last group is chiefly concerned with the protection of sewerage systems and treatment works.

Federal Control. The federal Water Pollution Control Act (Public Law 845) was enacted in 1948 and is the first water pollution control law enacted by the Federal Government, although measures had been proposed in Congress many times previously. The law does not provide for any direct control over water pollution by the Federal Government and recognizes the primary responsibility and the rights of the state in controlling water pollution. However, it does provide for the federal regulation of pollution on interstate rivers with state consent. The act also provides for (*a*) support and aid to technical research to devise and perfect methods of treatment of industrial wastes, (*b*) federal technical services to state and interstate agencies, and to industries, and (*c*) financial aid to state and interstate agencies and to municipalities in the formulation and execution of their stream pollution abatement programs. A second section of the act requires the Surgeon General of the U.S. Public Health Service to prepare comprehensive programs for the abatement of pollution in interstate waters for practically all water uses.

State Control. Almost every state has some type of legislation for the control of pollution and most have given the responsibility for pollution control to some state agency such as the State Health Department, the Fish and Game Commission, or a specially constituted water pollution control agency. In some states the responsibility is divided between two or more departments each having assigned to it special areas of pollution control. Where new state legislation has been enacted, the trend has been toward the formation of special water pollution control boards leaving with the State Health Department the responsibility for only those matters concerning or affecting health.

Although most states have some type of pollution control legislation, many have set no standards or criteria for the control of streams or effluents discharged into the

streams. Where standards have been established they have usually been set by the control agency under powers delegated to it by the state legislature.

Special Interstate Pollution Control Commissions. Because many important streams and coastal waterways are interstate, it was not possible to achieve effective pollution control without close cooperation between the states involved. Even where the spirit of cooperation existed, the conflicting interests of the several states has often prevented the solution of pressing pollution problems.

Many of these conflicts have been resolved by the creation of an interstate agency responsible for the establishment, and often enforcement, of minimum stream standards within the area under their jurisdiction. Thus, each state gives up some sovereignty and delegates some of its authority to the control commission, which is responsible for pollution control on a regional basis for the common good. There are many variations, particularly in the amount of control delegated to the commission. The Interstate Sanitation Commission controlling coastal waters for New Jersey, New York, and Connecticut in the New York metropolitan area is charged with the enforcement of pollution control regulations. Conversely, the Interstate Commission on the Delaware River (Incodel) acts only as a coordinating and advisory agency and the control regulations and enforcement remains an individual state responsibility, but subject to the requirements of the reciprocal agreement entered into between the states of Delaware, New York, Pennsylvania, and New Jersey.

Other interstate pollution control organizations include:

The International Joint Commission created in 1909 by treaty between the U.S. and Great Britain and empowered to hear disputes and conduct investigations regarding pollution of U.S. and Canadian boundary waters and streams flowing across the boundaries.

The Interstate Commission on the Potomac River Basin was established by a compact between Maryland, Virginia, Pennsylvania, West Virginia, and the District of Columbia as a coordinating body to recommend minimum standards of sewage and industrial waste treatment to the signatory states.

The New England Interstate Water Pollution Control Commission was formed in 1946 by compact between Connecticut, Massachusetts, and Rhode Island and has since been joined by New York, Vermont, and New Hampshire. The compact requires each state to classify its interstate streams according to their highest use, submit the classifications to the commission for approval, and then establish treatment and pollution control programs to bring about the improvements required to meet the approved classifications.

The Ohio River Valley Sanitation Commission was established by compact between the states of Illinois, Indiana, Kentucky, New York, Ohio, Pennsylvania, West Virginia, and Virginia for the purpose of cooperative control of pollution in the Ohio River drainage basin. The Commission is authorized to adopt, prescribe, and promulgate rules, regulations, and standards for administering and enforcing pollution control measures. Each signatory state agreed to enact necessary legislation and adopt enforcement measures to meet the objectives of the compact.

Stream Pollution Control Standards. Standards or regulations can usually be classified under one or more of the following headings: (*1*) effluent quality; (*2*) stream quality; (*3*) stream use classification, with special stream and effluent quality standards for each classification, and (*4*) special regulation for each case after adequate study.

The latter two classifications are special cases of the first two, but they have been given special mention because their use permits greater flexibility of control programs and they also represent the two most advanced approaches to stream pollution control.

Effluent standards are the easiest to administer and control, and are popular with some regulatory agencies. Although effluent standards are often more rigid than other types, they are preferred by some industries because they are clearly defined and have fewer uncertainties for the financing, administration, and operation of their industrial waste treatment programs. Effluent standards have certain disadvantages: (*1*) they are usually too rigid during periods of normal stream flow because they must be set to protect the stream during low flow periods, (*2*) they are concerned only with the concentration of the pollutant and disregard the volume of flow and the total amount of the pollutant discharged, (*3*) they tend to promote inequities between various stream users because a relatively unimportant small volume of concentrated waste may require a very extensive treatment to meet the standards while a very important large volume of dilute waste may require only perfunctory treatment.

Stream standards apply to the quality or condition of the stream waters after receiving a waste, and their stringency reflects the uses to which the receiving waters are put. Stream standards appear more realistic because the required effluent quality is dictated by the condition and flow of the stream. Theoretically, maximum treatment would be required only during periods of minimum flow and less extensive treatment could be provided during periods of average or higher flow. There are several disadvantages which work against the use of stream standards alone for pollution control. (*1*) The regulation of effluents to conform to stream specifications is very difficult because extensive stream surveys are required to obtain the necessary control information. (*2*) When several effluents are discharged into a stream, the interpretation of the data and the fixing of responsibility for below-standard stream conditions is very difficult and administration of a control program is often handicapped. (*3*) A prior upstream user may pre-empt the available purification capacity of a stream and subsequent downstream users may be forced to a high degree of treatment to prevent deterioration of the stream below the specified conditions.

Attempts have been made to obtain stream pollution control and avoid the pitfalls encountered with both effluent and stream standards. In New York and several other states streams and coastal waters are first classified according to their best use. Stream specifications are set for each section so that the waters will be satisfactory for the highest use specified. After all streams are classified, the amount of pollution allotted to each user will be determined after study of the general problem in each area. The required effluent quality will be judged according to the needs and without setting arbitrary standards. For this purpose, a water pollution control board was set up within the framework of the New York State Department of Health. California has established regional stream pollution control agencies, and has recently enacted some of the most modern pollution control legislation. The authorities recognized that the involved problems of stream pollution are not susceptible to good control by simple control legislation using rigid standards. The legislation enacted requires that each pollution problem be considered separately, and that effluent requirements be set only after individual study of each problem. General water quality criteria have been set for the guidance of the pollution control boards, but each case is judged on its merits after thorough study.

Local Control. At the local level, control of industrial wastes is concerned with

their discharge into sewerage systems. The chief purpose of this control is to protect the structures from damage, safeguard the operation of the system and treatment works, and prevent the discharge of materials deleterious to the receiving waters. Most sewerage systems have some type of control over waste discharges, usually by ordinance, but often the exercise of this control is only perfunctory. In general, two types of control regulations are used. One type is general and merely prevents the discharge of wastes which will be harmful to the structures, plant operation, or the receiving stream. The other type is very specific about the kinds of materials that cannot be discharged, and limits the concentration of many common constituents of wastes. Unfortunately, restrictive controls are often unrealistic and overrestrictive. Studies have shown that if some controls were rigidly applied, ordinary household sewage could not be discharged into the sewers.

Bibliography

The references in the industrial waste field are very extensive and scattered in many sources. Fortunately, the *Sewage Works Journal*, and its successor *Sewage and Industrial Wastes*, gives each year a review of the significant literature in the whole wastes field together with a complete bibliography.

The following are the references to industrial waste bibliographies found in the above journals:

Sewage Works J.: **7**, 713 (1935); **8**, 187 (1936); **9**, 153–163 (1937); **10**, 196 (1938); **11**, 181 (1939); **12**, 227 (1940); **13**, 223 (1941); **14**, 351 (1942); **15**, 226 (1943); **16**, 260 (1944); **17**, 251 (1945); **18**, 267 (1946); **19**, 231 (1947); **20**, 251 (1948); **21**, 245 (1949).

Sewage Ind. Wastes: **22**, 618 (1950); **23**, 585 (1951); **24**, 579 (1952); **25**, 633 (1953); **26**, 695 (1954).

GENERAL REFERENCES

(1) Besselievre, E., *Industrial Waste Treatment*, McGraw-Hill, N.Y., 1952.
(2) Eldridge, E. F., *Industrial Waste Treatment Practice*, McGraw-Hill, N.Y., 1942.
(3) Hart, W. B., *Industrial Waste Disposal for Petroleum Refineries*, Petroleum Processing, Cleveland, Ohio, 1947.
(4) Hodgson, H. J. N., *Sewage and Trade Wastes Treatment*, Frank Trigg, Govt. Printer, No. Terrace, Adelaide, Australia, 1938.
(5) Rudolfs, W., *Industrial Wastes* (A.C.S. Monograph No. 118), Reinhold, N.Y., 1953.
(6) Southgate, B. A., *Treatment and Disposal of Industrial Waste Waters*, His Majesty's Stationery Office, London, 1948.
(7) Wilson, H. M., and Calvert, H. T., *Trade Waste Waters*, Charles Griffin, London, 1913.

SPECIAL LITERATURE REVIEWS

Doudoroff, P., and Katz, M., "Critical Review of Literature on the Toxicity of Industrial Wastes and Their Components to Fish": I. Alkalies, Acids, and Inorganic Gases, *Sewage Ind. Wastes*, **22**, 1432 (1950); II. The Metals, as Salts, *Sewage Ind. Wastes*, **25**, 802 (1953).

INDUSTRIAL WASTES SYMPOSIUMS

(1) *Ind. Eng. Chem.*, **44**, 467–552 (1952).
(2) *Ind. Eng. Chem.*, **39**, 557–682 (1947).
(3) *Proc. 1st Ind. Waste Utilization Conf.*, 1944; *Proc. 2nd–9th Ind. Waste Conf.*, 1946–54.

H. E. Orford, W. B. Snow, and W. A. Parsons

WATER

Water is the most abundant compound at the earth's surface and the most important. Appreciation of its importance and representative character led to its inclusion, along with air, earth, and fire, in the earliest list of elements. No sample of water, however, is wholly pure and wholly typical. Wholly pure water remains an unattainable ideal although samples of very high purity, certainly of sufficient purity for most purposes, can be prepared by standard and well-known methods. The ready availability of water and its relatively easy purification have led to the choice of water as a standard in a variety of measurements. Its density provided at one time the connection between the metric units of mass and length. It still furnishes the basis for the common scales of temperature and for the units of heat energy, specific gravity, and specific heat.

Many of the properties of water are extremes or nearly so. Its dielectric constant, for example, is unusually high, as are its surface tension against air, its specific heat, and its heats of evaporation and fusion when calculated per unit of weight. The last two values are high because of the low weight of the water molecules. The heats of evaporation and fusion on a molar basis are normal for substances that freeze or boil near 0 or 100 °C., respectively. Some other properties seem more nearly normal also when given per mole rather than per gram.

The frequently reported slight but strange variability in the properties of water is probably to be expected when one considers the unusual precision often sought in a study of water. The variable isotopic composition of samples of water (see p. 925), and slight extraneous effects become important under such conditions. Exactly the same complications would probably be apparent if the properties of other substances were measured with similar precision.

In the discussion that follows, the term water refers to water in which the isotopes appear in their natural relative abundances.

Those properties of water that have the greatest utility in engineering practice are given in numerous well-known reliable compilations (12,14,17,22). No effort is made here to duplicate available tables and graphs nor to comment on all the available data. The present treatment is both selective and arbitrary. An interesting general survey of the properties of water constitutes the material in a very useful and critical book by Dorsey (5) which is referred to many times here.

Vapor

Size and Shape of Molecules. Water vapor behaves nearly but not exactly as an ideal gas of molecular mass 18.016. The departure from ideality in the saturated vapor around 100 °C. is a matter of a few per cent. The deviations are those to be expected if water forms clusters to a slight extent, the clusters being mostly dimers and tetramers, $(H_2O)_2$ and $(H_2O)_4$. The van der Waals equation provides a better approximation to the actual behavior of water vapor than do the ideal gas laws. It may be written for n moles of vapor in the following form:

$$\left(p + \frac{an^2}{v^2}\right)(v - nb) = nRT$$

where p is the observed pressure, v the volume, T the temperature (°K.), R the gas constant, and a and b the van der Waals constants. For water, a is approximately

0.01089 and b is 0.001362, where p is expressed in atmospheres, and the volume at 0°C. and 1 atm. pressure is taken as 1.

The van der Waals b is the "excluded volume" and for spherical molecules is four times the molal volume. Thus b gives a rough indication of the "effective" size of molecules even when the molecules are planar like H_2O rather than spherical. Several other sources of information give an indication of size also, and some of them suggest the geometry of the molecules as well. Kinetic theory, for example, leads to an expression for viscosity as a function of molecular "diameter." The viscosity of water vapor points to a molecular diameter of about 2.9 A. (2.9×10^{-8} cm.) (ref. 17, Vol. I, p. 121). Other methods of estimating the diameter produce different values. Dorsey's tabulation includes results as low as 2.34 A. and as high as 6.4 A., exclusive of some extreme values based on the effect of water vapor on the emission of light from excited mercury molecules (ref. 5, p. 43).

Information concerning the *shape* of gaseous water molecules comes principally from spectra (emission, absorption, and scattering) and dielectric constants. The results suggest that the two O—H bonds in water are in every way equivalent to each other. The bonds intersect at an angle (about 105°) which is very close to a tetrahedral-bond angle (that is, 109° 28′, which is the angle made by two lines drawn from the center to two corners of a regular tetrahedron). As a consequence of their nonsymmetrical character, water molecules are electrical dipoles, that is, the centers of action of the positive and negative charges in water molecules do not coincide. Their dipolar nature leads water molecules to attract each other rather strongly, actually more strongly than do most other lightweight molecules. Water is not greatly different, however, from ammonia and from hydrogen fluoride in this respect. Discussions of the relation of the bonds in water molecules to the wave functions of the valence electrons in oxygen and hydrogen atoms may be found in many books (21,25,26). The extent of the electrical asymmetry in water molecules and in polar compounds generally is not large and corresponds to the displacement of about one electron charge (4.80×10^{-10} e.s.u.) through a distance of 1A. The dipole moment of water molecules has a value harmonious with this idea (1.84 Debye units).

The O—H interatomic distance in gaseous water is about 1.1A. (ref. 25, p. 135). This value applies to a nonrotating and nonvibrating molecule. Rotation subjects the molecule to centrifugal forces, and under the influence of these forces molecules stretch. The amount of stretching depends on the violence of rotation and on the force constant tending to restore the displaced atoms to their resting or equilibrium positions. The same force constant, together with the masses of the atoms, determines the frequency of vibration. It has been possible to accumulate knowledge concerning the binding forces in water molecules. For small displacements, Hooke's law applies, but for larger displacements the restoring constant diminishes and the accompanying vibrations are nonharmonic. The nonharmonic constants have also been evaluated.

An interesting concept introduced by quantum mechanics is that the energy of a harmonic vibrator is limited to the discrete values recorded in the equation:

$$E_{\text{vibr.}} = (n + \tfrac{1}{2})h\nu$$

where n is a quantum number which may have only integral values from 0 upward, h is Planck's constant (6.625×10^{-27} erg-sec.), and ν is the vibration frequency characteristic of the vibrator. This formulation indicates that the energy of a vibrating sys-

tem never equals zero, even when $n = 0$. At 0°K. a harmonic vibrator will have vibrational energy to the extent of $\frac{1}{2}h\nu$—the so-called zero-point energy. A number of observations on dissociation energies and on the comparative rates of chemical reactions become clear in the light of this idea. Not one but three fundamental frequencies corresponding to three independent modes of vibration are characteristic of water molecules. These frequencies and the principal moments of inertia appear in Table I (31).

TABLE I. Some Properties of Water Molecules.

Property		H_2O	D_2O
Fundamental frequencies, cm.$^{-1}$	1.	3825.32	2758.06
	2.	1653.91	1210.25
	3.	3935.59	2883.79
Principal moments of inertia, 10^{-40} g.-sq.cm.	1.	1.0029	1.790
	2.	1.9320	3.812
	3.	2.9769	5.752

Heat Capacity. The heat capacity of gaseous water is about the value expected on the basis of the equipartition principle, which suggests that on the average each degree of freedom in a molecule has associated with it energy equal to $\frac{1}{2}\,kT$, where k is Boltzmann's constant (1.380×10^{-16} erg/(molecule)(degree)) and T is temperature in degrees Kelvin. At ordinary temperatures, water has six degrees of freedom: three corresponding to translational movement and three to tumbling or rotation. The heat capacity is, therefore, about 6 cal./(mole)(°C.). The value rises with increasing temperature because energy goes also into causing increased vibration and, at still higher temperatures, into electronic excitation as well. Empirical equations and tables giving the heat capacity as a function of temperature up to several thousand degrees appear in numerous handbooks and in reference (5, pp. 92–102).

Electrical Properties. Water vapor in the absence of ionizing radiations is a good insulator, provided the electrical field is inferior to a critical quantity known as the electrical strength of the vapor. This *electrical strength* is about 345 volts/cm. for water at a pressure of 0.16 mm. and a temperature of 22°C. Water vapor seems to be perfectly normal in this respect. The actual voltage at which measurable currents pass through the vapor depends on many experimental details. When an electrical discharge occurs in water vapor, chemical changes result which include the formation temporarily of hydrogen atoms and hydroxyl radicals, some of them in excited states. The presence of water may influence the products formed from discharges through other gases.

An important quantity in gaseous conduction is the *ionization potential.* For water the value is about 13 e.v., which means that an electron accelerated through a potential of 13 volts would have enough kinetic energy to release an electron from a water molecule, leaving an H_2O^+ ion. For many polyatomic molecules, ionization potentials lie between 10 and 15 e.v.

Thermodynamic Properties. The thermodynamic characteristics of water vapor and in particular the standard enthalpy change during formation from the elements (ΔH_f^0), the free energy of formation (ΔF_f^0), and the standard entropy ($S°$) have considerable importance in chemical and engineering calculations. These quantities continue to receive attention from many authors. The best values are comprised in a

tabulation of the Bureau of Standards (28), which represents an extension of a work started by Bichowsky and Rossini (1). Values for water as given in reference (28) are shown in Table II.

TABLE II. Thermodynamic Value for Ordinary Water.

Property	Vapor	Liquid
Heat of formation, ΔH_f^0, kg.-cal./mole		
At 0°K.	−57.107	—
At 298.16°K.	−57.7979	−68.3174
Free energy of formation, ΔF_f^0, kg.-cal./mole, at 298.16°K.	−54.6357	−56.6902
Equilibrium constant of formation, $\log_{10} K_f$, at 298.16°K.	40.04724	—
Entropy, S^0, e.u., at 298.16°K.	45.106	16.716

The values shown in Table II can be combined with other thermodynamic values in a variety of applications. The magnitude of the logarithm of the equilibrium constant for water synthesis indicates that water is thermodynamically a stable substance, dissociating under ordinary conditions to a negligible extent. Above 2000°K., the vapor becomes less stable, particularly at low pressures. Dissociation into H_2 and OH is possible as well as into H_2 and O_2. The percentage of dissociation at 1 atm. rises from about 0.6 at 2000°K. to 14.1 at 3000°K. and to 58.7 at 5000°K. The latter figures represent extrapolations. Even in the high-temperature range, ionization of water vapor remains unimportant because of the great energy required for the process, estimated to be near 370 kg.-cal./mole. The specific rate of dissociation of water vapor into H_2 and O_2 at 2000°K. is probably too high for any direct measurement, and the slight degree of dissociation is the result of very rapid recombination of the elements at this temperature.

Liquid

Structure. The structure of liquids in general and the structure of water in particular continue to be the cause of much dispute. Some scientists believe that the liquid is composed of definite polymers. Eucken, for example, claims that at 0°C. few simple molecules exist in the liquid but that $(H_2O)_2$, $(H_2O)_4$, and $(H_2O)_8$ are present in about equal amounts, forming an ideal solution (6). Others conclude that water has a semicrystalline structure not composed of definite species of associated water. This is the current and prevalent view. Lennard-Jones and Pople have proposed a theoretical description according to which nearly all the molecules have four bonds (18,23). These bonds are constantly being bent, broken, and re-formed. This view leads to predicted values of certain properties in keeping with experiment. A study of diffusion, however, has led Wang to state that water at room temperature is only slightly more than two-coordinated (30). A wholly satisfactory model of the liquid state remains elusive, for in liquids molecules have neither the good order characteristic of solids nor the randomness and independence of molecules in the gaseous state.

An interesting feature of the structure of liquids is their "free volume," which on a per molecule basis is the space through which the center of gravity of a molecule can move without the molecule colliding with other molecules. The free volume has been of particular usefulness in interpreting the viscosity of liquids (20).

Effects of Compression and of Heating. The compressibility of water and the expansion of water on heating have received much study. Reference (5) includes many tables of pertinent data. A well-known and striking property of water is the small but definite contraction it shows when heated at temperatures below 4°C. The extent of the contraction is small and amounts to just more than 1 part in ten thousand in the interval 0–4°C. This contraction is often attributed to a breaking down of ice structures that persist in the liquid at temperatures near the melting point, but the greater density of water as compared to ice has never been quite satisfactorily explained. The tetrahedral structure of ice is said to be rather open and thus it leads to a low density of ice. But it is not entirely clear why the tetrahedrally bound molecules in the liquid phase form a more compact structure than the solid. The expansion that accompanies freezing means that the potential energy as a function of average distance between molecules qualitatively follows a course shown schematically in exaggerated form in Figure 1.

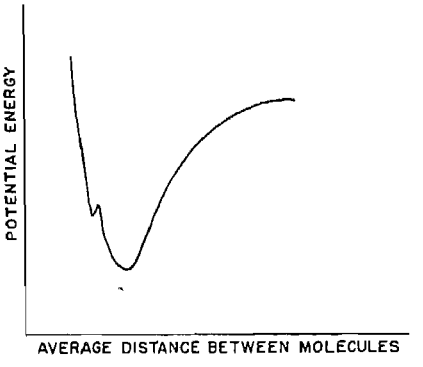


Fig. 1. Variation of potential energy in condensed water as a function of average separation.

The temperature at which water shows a maximum density varies with pressure and with the concentration of dissolved substances. The temperature is lowered by raising the pressure or by adding solute as if these influences promote destruction of ice structures in water.

Vapor Pressure. The vapor pressure of water follows a normal course as a function of temperature, although the values are lower than for most substances of so low a molecular weight. The large dipole moment of water and the extensive hydrogen bond formation in the liquid state lead to a large heat of vaporization and hence a relatively low vapor pressure. The *entropy of vaporization*, that is, the heat of vaporization (9720 cal./mole at 100°C.) divided by the temperature at the boiling point (373.16°K.) is larger than for liquids without such extensive hydrogen bonding. The term hydrogen bond refers to the attraction that a hydrogen nucleus in one molecule exerts on a negatively charged region of a different molecule. The very large entropy of vaporization of water reflects the greater degree of organization that hydrogen bonding gives liquids in comparison with the less well organized "normal" liquids that lack hydrogen bonding. Another name for entropy of vaporization (at the normal boiling point) is *Trouton's constant*. For water the constant is 26.1 cal./(deg.)(mole), but for most liquids the value is near 20.6.

The vapor pressure of small droplets of liquid is greater than that of large drops, as shown by Lord Kelvin in 1870. Experiment and theory as applied to the evaporation of small droplets of water are in good agreement. Vapor pressures are greater also when fluids are compressed, as by pumping an inert gas into contact with them. The effect is not large but it falls in a measurable range. At 0°C. it amounts to about 0.61 mm. per atmosphere of applied pressure and to about one fourth of this at 70°C. Some investigators refer to this increase as being due to a kind of dissolving of water vapor by the inert gas. It is probably simpler to regard the enhanced tendency to evaporate as due to a compression of the surface layer of the liquid so that more molecules are in a position to evaporate. In some engineering situations, it is necessary

to keep in mind the effect of radius of curvature of droplets and the effect of enhanced pressures in promoting the evaporation of water.

The effect of solutes in diminishing the vapor pressure of water is well known. In dilute solutions, Raoult's law applies. Although the law is empirical, it provides the basis for much of the analysis of colligative properties of solutions. Raoult's law states that the vapor pressure of a pure solvent is equal to its vapor pressure from a solution divided by the mole fraction of the solvent in the solution. When applying the law to solutions of electrolytes, ionic dissociation must be taken into account in calculating the mole fraction of solvent.

Tensile Strength and Internal Pressure. An interesting property of any liquid, including water, is its *tensile strength.* It is difficult to measure this property accurately, but it is well established that liquids can sustain fairly large loads. The difficulty of measurement arises from the possibility that a parting of the liquid may occur at a minute gas bubble or at the container-liquid interface so that the break is not wholly characteristic of the liquid. Water has been observed to sustain tensions of more than 50 atm.

One may picture the tension of a liquid as operating against an *internal pressure,* by which is meant a net effective pressure arising from molecular attractions which tend to hold the liquid together. The several ways of estimating such pressures include an application of van der Waals' equation to the liquid. The variously computed pressures do not agree. At room temperature, the value in water is about 12 atm. The value diminishes at higher temperatures. The difference between this value and the tensions of more than 50 atm. which water can sustain indicates that this subject is in need of further study, and that factors other than internal pressure may contribute to the tensile strength (ref. 5, p. 181).

Surface Tension. The study and the measurement of surface tension have been of interest since the time of Leonardo da Vinci. Several methods of measurement are familiar but most of them are susceptible to error and not altogether easy to interpret. The surface tension is of importance in the spreading of films, the formation of foams, the wetting of surfaces, and the like. The surface tension of water against air (72 dynes/cm. at 25°C.) is larger than that of most common substances, but it is less than that of metals and of molten salts. The surface tension approaches zero in the neighborhood of the critical temperature.

Solutes fall into two groups as far as effect on surface tension is concerned. One group (capillary inactive) has little influence on the surface tension. The other (capillary active) produces a large lowering of surface tension. Solutes of the second type appear in larger concentration in the surface layer than in the bulk of solution: they are said to be adsorbed in the surface. Soap provides an example of a capillary active solute, whereas most inorganic salts belong to the capillary inactive group.

Electrical Conduction. While the dissolution in water of substances identified as electrolytes causes an increase in electrical conduction, even the purest water conducts to a slight extent. Entirely pure water, being an abstraction, can hardly be the subject of actual experiments, but by very careful repeated distillation, Kohlrausch and Heydweiller (1894) obtained a sample of water whose conductivity was only 4.2×10^{-8} ohm^{-1} cm.$^{-1}$ at 18°C. This value exceeds by 10% the theoretical conductivity computed from the equivalent conductances of H^+ and OH^- ions and the ion product, K_w, of water. In contact with air, water dissolves carbon dioxide and the conductivity rises at 25°C. to about 8×10^{-7} ohm^{-1} cm.$^{-1}$.

The *ion product* of water, that is, the product of the H^+ and OH^- concentrations, may be determined from the electromotive force of cells that include a hydrogen electrode, and independently from the extent of hydrolysis of salts. The various results are in good agreement with each other and the results at 25°C. average 10^{-14} when the concentrations are expressed in molar units. The pH scale is based on this result. Neutrality, therefore, at room temperature means a pH of 7.0. K_w at 100°C. is 52×10^{-14}.

Solvent Power. In technology, the solvent powers of a liquid probably exceed in importance all others. While the principles of the phase rule suggest the idea that every phase has at least a small solubility in every other, there is no universal solvent in the sense that a given liquid will dissolve easily observable amounts of everything else. Probably molten acetamide (or perhaps formamide) is closer to being a universal solvent than is water. Water remains the cheapest and most convenient solvent, but like all solvents it exhibits unique properties.

Water dissolves many "inert" gases, such as hydrogen and several of the atmospheric gases, to about an equal extent in terms of molar concentrations. Extensive tables in I.C.T. (14) and in Dorsey (5) comprise the principal data. The solubility in these cases may be viewed as physical. Gases that dissolve more extensively than these, some of them like the hydrogen halides thousands of times more extensively, in general react chemically with the water and make the water either acidic or basic depending on the gas.

Solids of low vapor pressure that do not react with water should have small solubility in water. If the solid can enter into chemical reaction with water, its solubility may be high. In general, electrolytes react strongly with water and their solubility may be large. Thus potassium acetate, potassium fluoride, potassium formate, lithium chlorate, and silver perchlorate show especially great solubility in water, but some of the heavy metal oxides and sulfides have only minute solubilities in water. The process of dissolving an ionic solid in water may be pictured as (*1*) an "evaporation" of ions from the solid, and (*2*) hydration of the ions. The first operation utilizes energy; the second releases energy. Both energy terms are large. If the energy released in the second process greatly exceeds the energy required in the first, large solubility will be expected. If the reverse is true, solubility will be small. Electrolytes are less soluble in solvents of smaller dielectric constant than in water and more soluble in solvents of larger dielectric constant. A rough rule indicates a proportionality between solubility and the cube of the dielectric constant (24).

Effects of Radiation. While water is ordinarily regarded as transparent, Dorsey (5) points out that the range of good transmission of radiant energy by water does not extend far beyond the range of visible light. Water is transparent from wave length 0.17μ to 1.0μ. Radiation of wavelength 0.165μ, that is 1650A., causes decomposition (5), but impurities may sensitize water to longer wavelengths (27).

Ionizing radiations in the form of α-, β-, γ-, and x-rays or streams of fast-moving neutrons, protons, and other charged particles bring about decomposition of water into hydrogen, hydrogen peroxide, and oxygen. Often a steady state is reached where the rate of decomposition just matches in rate the resynthesis of water. When γ-rays or x-rays cause the decomposition, the concentration of products in the steady state is sometimes too low to be detected (that is, about 1 micromole/liter). With other types of radiation the products are generally easily detectable. Dissolved materials may affect the steady-state concentrations.

Ice

Structure. The form of snow and ice crystals has long proved to be a fascinating subject. While the gross forms vary greatly, the same lattice structure is found in all ordinary ice and snow, namely, a tetrahedral arrangement of the water molecules. The symmetrical 6-sided dendritic crystals familiar as illustrations on Christmas cards are special forms. These develop only at −15°C. with more than 10% supersaturation. At either higher or lower temperatures, plates, bullets, needles, and scrolls appear (19). Other vapors influence the growth patterns also. Silver iodide smoke particles act as condensation nuclei for ice crystals, and thus the smoke has proved useful in the seeding of supercooled clouds (that is, clouds whose temperatures are below 0°C.) with the idea of inducing rainfall.

Effect of Pressure. The melting of ice under pressure results from the expansion of water during freezing. The effect is quantitatively rather small: one atmosphere of pressure lowers the melting point by 0.0075°C. Although the possibility of skating on ice and the flow of glaciers have frequently been attributed to this melting under pressure, the principal effects must be explained in some other way. In skating it is probably melting induced by surface friction that leads to slippage, and in glacial movement, plastic flow of the solid. The drawing of a weighted wire through a block of ice at 0°C., however, is due to the effect of pressure on melting. The block refreezes above the wire as the pressure is released, so that the block is not severed by the movement of the wire. This process is known as regelation.

A study of the behavior of materials under high pressure, much of it under the direction of P. W. Bridgman, has revealed the existence of several forms of ice in addition to the common form (ice I). The regions of existence of the several types of ice is indicated in Table III (4, ref. 14, Vol. IV, p. 11) which shows pressures and temperatures of the various triple points, that is, the points where three phases exist in equilibrium with each other.

TABLE III. Triple Points of the Ices.

Phases[a]	Temp., °C.	Pressure, atm.
G, L, I	0.0075	0.00602
L, I, III	−22.0	2045
I, II, III	−34.7	2100
L, III, V	−17.0	3420
II, III, V	−24.3	3400
L, V, VI	+0.16	6175
L, VI, VII	81.6	21,700

[a] G refers to gas, L to liquid, I to the first form of ice, etc. Ice IV may have no region of stable existence.

Effect of Radiation. Under the influence of ionizing radiations, water decomposes in the solid state as well as in the fluid states. On melting ice that has been exposed to ionizing radiations, hydrogen and hydrogen peroxide are released but in somewhat smaller yield than in liquid water. Radicals or other reactive centers that are formed in the ice at low temperatures may enter into reaction as the temperature is raised.

Chemistry of Water

Catalysis. Both water vapor and water liquid are important catalysts. In the vapor phase, for example, well desiccated ammonium nitrate at 300°C. does not

decompose appreciably into nitrous oxide and water. Moist ammonium nitrate, however, decomposes rapidly at 180°C. (9). A trace of moisture (0.33%) will lower the second explosion limit of CO + O_2 mixtures in silica vessels by as much as 100°C. (11). But water is not a universal catalyst, as has occasionally been stated.

Sometimes the catalytic action of water arises from condensed films. Such films are probably important in the corrosion of metals.

Since solutes in a liquid solution have far more mobility than in the solid state, they are as a rule much more reactive when dissolved. If finely powdered potassium iodide and mercuric chloride are mixed, a slight pink color indicates that there has been a perceptible amount of reaction to form mercuric iodide. If a drop of water is added, a copious red precipitate will appear, indicating a very rapid reaction. Any liquid that dissolves the reactants to a significant extent would function as a catalyst in the same way. It is not at all necessary that the solvent promote ionization if it is to act as a catalyst in such reactions. Many double decompositions occur with great rapidity in nonaqueous, "nonionizing" solvents.

Reactions. Water acts as an oxidizing agent toward active metals (those above hydrogen in the activity series) and toward some salts (for example, chromous chloride), and as a reducing agent toward active nonmetals (for example, the halogens) and some compounds (for example, potassium permanganate and derivatives of divalent silver). Water enters also into many hydrolytic reactions with a wide variety of compounds, including the phosphorus halides and organic esters.

A reaction of general occurrence is *hydration*, that is, the formation of stable addition compounds with other substances. Sometimes the hydrates have low stability and may be decomposed easily, like $Na_2CO_3.10H_2O$. Sometimes they have great stability as do $Na_2O.H_2O$ and $P_2O_5.H_2O$. Other polar compounds like ammonia, hydrogen peroxide, and ethylene diamine also form numerous addition compounds. In forming addition compounds, water is not at all unique. Some of the products formed by addition of water to other substances are solids of variable composition. These products are solid solutions rather than compounds. They include the zeolites—silicates with rather open structure into which water can penetrate with little other change. Many rocks contain combined and adsorbed water in considerable amount. It is not possible to distinguish sharply between chemical combination and chemisorption.

Estimation and Detection. The identification of the impurities, living and nonliving, in natural and industrial water makes up a distinct field of much importance. See *Water* (*municipal*). The inverse problem of identifying and estimating water in the presence of other substances is also often of interest and importance. Reactions wholly characteristic of water are hard to find: its volatility, its release of hydrogen in presence of sodium, its formation of acetylene by reaction with calcium carbide, its combination with calcium chloride to give a stable addition product, and many other properties are shared by other substances as well. A nearly specific reaction, however, is one with the so-called Karl Fischer reagent (active ingredients: iodine, sulfur dioxide, and pyridine in dry methanol as solvent). The reaction of this reagent with water occurs in two consecutive steps whose sum amounts to:

$$H_2O + I_2 + SO_2 + 3\ C_5H_5N + CH_3OH \longrightarrow C_5H_5NHSO_4CH_3 + 2\ C_5H_5NHI$$

By use of this reagent, water in a large variety of materials can be determined in a fairly simple titration procedure (8, 18a, 29).

Isotopic Water

Because of the isotopic complexity of both hydrogen and oxygen, ordinary water is a mixture of several distinct kinds of molecules. The hydrogen atoms in water have relative masses of 1, 2, or 3 and the oxygen atoms masses of 16, 17, or 18. These isotopes combine to produce 18 distinct kinds of water molecules. Each isotopic variety of water has its own characteristic properties. In natural water, the proportions of the isotopes vary somewhat and some vagueness, therefore, attends use of the term "ordinary water." Variations in the isotopic constitution of water result in large part from differences in volatility. Consequently, the rain that falls in humid regions will differ in composition from that which falls in arid regions.

Not only does fractionation of the isotopes occur in nature but it occurs also, usually unintentionally, in the laboratory. Extreme care in purification of water is apt to change the proportions of the isotopes. Unless the purification is followed by an equilibration designed to reestablish the natural isotopic abundances, a sample with abnormal properties will result. Some of the frequently observed variability in the properties of water reflects such influences. The other chief source of variability is the presence of impurities in perhaps minute yet variable amounts. These impurities may be carried along with the water during purification or may be acquired before or during a measurement of some property.

Variations in the proportions of the several isotopes in water, while ordinarily small, are easily observable in mass spectrometers and in density measurements. Approximately one hydrogen atom in every 7000 in common water has mass 2 (16). The three stable isotopes of oxygen, namely O^{16}, O^{17}, and O^{18} occur in the average relative abundances 99.76%, 0.039%, and 0.204%, respectively. The preparation of water enriched with respect to one of the less common isotopes can be effected in any of several ways. Such enriched water proves useful for a variety of tracer experiments. The isotopically labelled water permits the location of a particular ingredient or its derivative in a process or identification of the source of a particular product. Practically pure "heavy water" (deuterium oxide), in which the hydrogen atoms have mass 2, is available at a present price of about one dollar per gram for small quantities, and of course at a lower unit price for larger amounts.

Heavy water is used in nuclear reactors (piles) to slow down or moderate the neutrons emitted in the reaction. The kinetic energy of these neutrons, at the time of their release from fissioning atoms, may exceed 1 M.e.v. per particle. Heavy water is often preferred to light water, in spite of the vastly higher cost of heavy water and the greater efficiency of light hydrogen atoms in energy moderation, because loss of neutrons by capture occurs to a considerably smaller extent in heavy water than in light water. In other words, heavy water is cheaper than neutrons.

Hydrogen atoms of mass 3, that is, tritium atoms, make up a small proportion of water that is not too "old." The proportion of T (tritium atoms) to H is always small, and for ground water gathered from Long Island and from New Jersey has been found to range from 3×10^{-18} to 10^{-15} (7). Water that has been stored for many years, for example glacial water, lacks a detectable content of tritium. The disappearance of the tritium is the result of its radioactivity, which transforms it into a helium isotope of mass 3. The half life of the tritium atoms is about 12.5 years (14a). All but 0.5% of the tritium in a water sample, therefore, would disappear during a century of storage.

The supply of "tritiated" water is constantly renewed as a consequence of the action of cosmic rays in the upper atmosphere, a region of most intense cosmic ray activity. The tritiated water falls as rain and its radioactivity at a later time reveals its residual content of tritium and hence the time that has elapsed since it left the atmosphere (15). Nuclear explosions probably add significantly to the supply of tritium oxide and thus introduce a complication into the determination of the age of water samples through measurement of their radioactivity. The β-particles emitted by tritium atoms cause water to decompose (13). In natural waters the effect is not directly detectable.

The large ratio of the atomic masses of H and T leads one to expect tritium oxide and protium oxide to show a greater spread in properties than any other pair of water species. The next greatest difference should be shown by deuterium oxide and protium oxide. The values of selected properties that make up Table IV suggest the extent of observed differences. Other values appear in Kirshenbaum's book (16).

Thermodynamic properties such as molal entropy, relative enthalpy, relative free energy, and heat capacity are also different for each species. Bigeleisen *et al.* have furnished tables to aid in estimating the magnitude of the differences (2,3).

TABLE IV. Selected Properties of Isotopic Water.

Property	H_2O	D_2O
B.p., °C.	100.00	101.41
F.p., °C.[a]	0.00	3.81
d_{25}^{25}	1.0000	1.1078
Temp. of max. density, °C.	3.98	11.22
Ion product (K_w) at 25°C. $\times 10^{14}$	1.00	0.20
Viscosity at 25°C., millipoises	8.93	11.00
Relative solubility in benzene at 25°C.	1.21	1.00

[a] Triple point for T_2O, 4.49.

Friedman and Haar have presented in tabulated form calculated thermodynamic functions for several isotopic water molecules in the temperature range 50–5000°K. (10).

Bibliography

(1) Bichowsky, F. R., and Rossini, F. D., *Thermochemistry of the Chemical Substances*, Reinhold, N.Y., 1936.
(2) Bigeleisen, J., *J. Chem. Phys.*, **21**, 1333 (1953).
(3) Bigeleisen, J., and Mayer, M. G., *J. Chem. Phys.*, **15**, 261 (1947).
(4) Bridgman, P. W., *J. Chem. Phys.*, **5**, 964 (1937).
(5) Dorsey, N. E., *Properties of Ordinary Water Substance* (A.C.S. Monograph No. 81), Reinhold, N.Y., 1940.
(6) Eucken, A., *Nach. Ges. Wiss. Göttingen Math.-physik. Kl.*, **IIa**, 38 (1946); *Z. Elektrochem.*, **52**, 6 (1948).
(7) Fireman, E. L., and Schwarzer, D., *Phys. Rev.*, **94**, 385 (1954).
(8) Fisher, K., *Angew. Chem.*, **48**, 394 (1935).
(9) Friedman, I., and Bigeleisen, J., *J. Chem. Phys.*, **18**, 1325 (1950).
(10) Friedman, A. S., and Haar, L., *J. Chem. Phys.*, **22**, 2051 (1954).
(11) Gordon, A. S., *J. Chem. Phys.*, **20**, 340 (1952).
(12) *Handbook of Chemistry and Physics*, 36th ed., 1954.
(13) Hart, E. J., *Ann. Rev. Phys. Chem.*, **5**, 146 (1954).
(14) *International Critical Tables*, Vols. I–VIII, 1926–33.
(14a) Jenks, G. H., Sweeton, F. H., and Ghormley, J. A., *Phys. Rev.*, **80**, 990 (1950).
(15) Kaufman, S., and Libby, W., *Phys. Rev.*, **93**, 1337 (1954).
(16) Kirshenbaum, I., *Physical Properties and Analysis of Heavy Water*, McGraw-Hill, N.Y., 1951.
(17) Landolt-Börnstein, *Physikalisch-chemische Tabellen*, 5th ed., 8 Vols. 1923–36 (photo-lithoprinted by Edwards Bros., Ann Arbor, Mich.).
(18) Lennard-Jones, J. E., and Pople, J. A., *Proc. Roy. Soc.* (London), **A205**, 155 (1951).
(18a) Mitchell, J., Jr., and Smith, D. M., *Aquametry*, Interscience, N.Y.-London, 1948.
(19) Nakaya, U., *Snow Crystals—Natural and Artificial*, Harvard Univ. Press, Cambridge, Mass., 1954.
(20) Partington, J. R., *An Advanced Treatise on Physical Chemistry*, Longmans Green, London, 1951, Vol. III, p. 94.
(21) Pauling, L., *The Nature of the Chemical Bond*, 2nd ed., Cornell Univ. Press, Ithaca, 1940, p. 78.
(22) Perry, J. H. (ed.), *Chemical Engineers' Handbook*, 3rd ed., 1950.
(23) Pople, J. A., *Proc. Roy. Soc.* (London), **A205**, 163 (1951).
(24) Ricci, J. E., and Davis, T. W., *J. Am. Chem. Soc.*, **62**, 407 (1940).
(25) Rice, F. O., and Teller, E., *The Structure of Matter*, Wiley, N.Y., 1949, p. 92.
(26) Rice, O. K., *Electronic Structure and Chemical Binding*, McGraw-Hill, N.Y., 1940, p. 269.
(27) Rollefson, G., and Burton, M., *Photochemistry and the Mechanism of Chemical Reactions*, Prentice-Hall, N.Y., 1939, p. 171.

(28) Rossini, F. D., Wagner, D. D., Evans, W. M., Levine, S., and Jaffee, I., "Selected Values of Chemical Thermodynamic Properties," *U.S. Natl. Bur. Standards Circ.*, **500**, 9 (1952).
(29) Smith, D. M., Bryant, W. M. D., and Mitchell, J., *J. Am. Chem. Soc.*, **61**, 2407 (1939).
(30) Wang, J. H., *J. Am. Chem. Soc.*, **73**, 4181 (1951).
(31) Yost, D. M., and Russell, H., *Systematic Inorganic Chemistry*, Prentice-Hall, N.Y., 1944, p. 273.

T. W. DAVIS

WATER, INDUSTRIAL AND MUNICIPAL

Industrial Water ..... p. 929
Municipal Water 946

See also *Wastes, industrial.*

All water used by man comes from the reservoir of the oceans. A small amount of sea water is used directly for cooling purposes in power plants or industries on the coast. Sea water and inland accumulations of brine also are used as raw material for production of chemicals such as salt, metallic magnesium and magnesium compounds, potassium compounds, and borates. Nearly all the water used, however, is fresh water which has been evaporated from the oceans, carried by the winds, and deposited as rain or snow upon the land, from there to return to the oceans.

The total quantity of fresh water available for use seems immense. On an average day, 4300 billion gallons of water fall on the United States. Of this amount about 70% is recycled to the atmosphere by evaporation or by the transpiration of vegetation. The remaining run-off, 1300 billion gallons per day, is the actual available supply of water (32). This supply is distributed, however, in a most uneven fashion. While precipitation over the U.S. averages 30 in. per year, the Olympic Mountains in the Pacific Northwest catch 160 in. During 1952, 86.94 in. fell at Blue Canyon, California, 9.64 in. at Bakersfield, California, and only 2.92 in. at Yuma, Arizona (38).

Like any other important raw material, water may have to be transported from the place where it is available to the place where it is needed for use. Thus, water is moved from the watershed of the Delaware River to supply New York City and from the Colorado River to supply Los Angeles and to convert the deserts of southern California into rich farm land. As the population continues to increase and industry to expand, it will become necessary to store more of the potential supply of water in reservoirs and to transport it to regions where it is needed.

In 1950, only one-seventh of the run-off of 1300 billion gallons was used for all human requirements. Table I summarizes the estimate of the President's Water Resources Policy Commission as to how this was utilized. Much of the water withdrawn by industry and by municipalities is not, however, "consumed," but is released as waste water or sewage to become again part of the supply. Cooling water is an example. Water used by industry for purposes other than cooling may have amounted to only 10 instead of the 70 billion gallons per day given in Table I (32).

Other interesting statistics were obtained in 1950 through a study made by the National Association of Manufacturers and The Conservation Foundation (22).

TABLE I. Estimated Consumption of Water for Various Purposes in the U.S., 1950.

Use	Consumption of water	
	Billion gallons per day	Per cent of total
Total	180	100
Irrigation	95	52.7
Industrial	70	38.9
Municipal	12	6.7
Rural (other than irrigation)	3	1.7

From 3,343 responses to approximately 15,000 questionnaires directed to the member companies of the N.A.M.:

(*1*) The total intake of the 3,343 plants was estimated to be 8 billion gallons of water per day. These plants comprised only 1.4% of the more than 240,000 plants in the U.S., but included 23.3% of the plants with more than 2500 employees.

(*2*) 163 plants, each taking in more than 10 million gallons per day, were found to be using more than three-fourths of the combined water intake.

(*3*) The "average" plant was calculated to be using one-quarter of its water intake for cooling, one-quarter for sanitary and service facilities, one-eighth for boiler feed, and three-eighths for process use. For plants taking in more than 10 million gallons per day, however, one-half was used for cooling and one-third for process, on the average.

The amount of water required to turn out a unit of product has been estimated for a number of industries. Selected items from a 1953 summary of available published information (19) are shown in Table II.

TABLE II. Estimated Water Requirements for the Production of Selected Commodities.

Commodity	Water required for production, tons water/ton commodity
Alcohol, industrial (190 proof)	60
Aluminum	8000
Ammonia, synthetic	130
Gasoline	10–15
Paper pulp	210–625
Soda ash	60–75
Steel	80–145
Sulfuric acid (100%)	15
Viscose rayon	750–830

The values in Table II generally represent operations before much attention had been paid to water management in industry. It is evident however, that even with the best re-use within a plant, from several to many tons of water will still be required to make a ton of any of these products.

Not only quantity but also quality of water is important. From a practical viewpoint, quality might be defined in terms of the relative freedom from difficulty during any specific use. This depends on the constituents carried by the water and what effects they produce when the water is pumped through a distribution system, heated in a heat exchanger, boiled in an evaporator or boiler, used to process textiles, or made into beer. Some of the more important constituents are included in Table III, which is intended merely to indicate the infinite variety of composition possible (40).

TABLE III. Character of a Few Surface and Ground Water Supplies.

Source	Dissolved constituents, p.p.m.								
	Dissolved solids	Hardness as $CaCO_3$	SiO_2	HCO_3	SO_4	Cl	Fe	Color	pH
Tuolumne River impounded in Hetch Hetchy Reservoir (San Francisco, Cal.)	13	9	3.8	7	1.6	1	0.02	—	6.4
Big Creek (Mobile, Ala.)	20	5	5	5	0.7	2.8	0.03	27	6.2
Catawba River (Charlotte, N.C.)	35	14	12	19	2.7	2.2	0.03	13	7.2
Lake Superior (Duluth, Minn.)	54	44	3.3	50	1	3.5	—	1	7.4
Green River (Tacoma, Wash.)	59	18	23	29	2	6.3	0	0	7.4
Delaware River (Morrisville, Pa.)	84	54	4.7	38	21	4.6	0.06	7	7.1
Well (Camden, N.J., Morris Well 3)	86	63	6.2	54	15	5.2	5.5	4	6.4
Wells (Memphis, Tenn., Parkway Field)	94	39	13	85	3.7	2.5	0.43	7	6.9
Brandywine Creek (Wilmington, Del.)	103	56	12	41	22	6.5	0.08	20	6.5
Lake Ontario (Oswego, N.Y.)	179	140	1.2	115	29	26	0.33	6	7.9
Wells (Long Beach, Cal.)	216	36	11	176	8.7	22	0.06	80	8.4
Mississippi River (New Orleans, La.)	262	175	10	161	51	24	0.36	—	7.5
Well (Fort Lauderdale, Fla., Hialeah Well 1)	330	252	6.8	255	39	22	1.7	—	7.3
Missouri River (Kansas City, Mo.)	365	221	12	192	120	19	—	—	8.3
Monongahela River (Clairton, Pa.—low flow)	—	184	—	0	304	9.6	—	8	3.5
Wells (Elizabeth City, N.C.)	405	182	41	208	29	83	8.1	23	6.7
Raccoon River (Des Moines, Ia.)	432	342	16	330	87	14	0.10	5	7.6
Mountain streams (Altoona, Pa.)	457	260	13	0	260	14	0.70	4	3.45
Wells (Manhattan, Kan.)	488	370	31	428	52	18	0.69	2	7.3
Colorado River impounded in Lake Havasu (Los Angeles, Cal.)	661	315	8	137	290	79	—	—	8.4
Wells (Hutchinson, Kan.)	853	352	16	255	125	230	0.0	0	7.3
Well (Dallas, Tex., Well 39)	1040	24	22	542	259	95	0.02	0	8.2

If rain falls on a mountain of rock from which it runs off rapidly as *surface water* into a river, it has only a slight chance to take anything into solution. The Tuolumne River in Yosemite National Park, which is impounded in the Hetch Hetchy Reservoir to supply San Francisco, picks up only 13 lb. of dissolved substances in a million pounds of water. The amount of finely-divided suspended solids also tends to be low.

In contrast, if rain falls steadily over the central plains, every stream begins to wash away particles of soil at an accelerated rate. The burden of suspended solids becomes high, as do the substances in solution. In Table III, the Missouri River at Kansas City is an example. Part of the rainfall, however, soaks into the soil, through which it may percolate for hundreds of miles as *ground water*. In so doing, it has an opportunity to pick up dissolved solids by contact with various minerals. When pumped from a well tapping the underground flow, it might show almost any analysis

from the relatively soft water of Memphis, Tennessee, to the hard and saline water of Hutchinson, Kansas, or the soft but still more heavily loaded water of well 39 at Dallas, Texas.

Surface water normally becomes saturated with oxygen, carbon dioxide, and other gases from the air. In well-populated regions, either raw sewage or the effluent from treatment plants is contributed to the water. Likewise, the water may carry wastes from extremely varied industrial operations.

Ground water in general shows little dissolved oxygen and little contamination by sewage or industrial wastes. It may, however, contain considerable carbon dioxide.

Each of the substances carried as suspended solids, dissolved solids, or dissolved gases influences in various ways the behavior of the water when it is employed for different specific purposes. In a very real practical sense, water is not just water, but is characterized by the dissolved and suspended substances it contains.

INDUSTRIAL WATER

Procurement

A company seeking a location for a new industrial plant must consider the resources of surface and ground water as carefully as the cost of energy and the materials to be processed. Is the supply of water adequate? At all times during the annual cycle? For the future, as well as now? What troubles will the available water cause in the operation of the plant? If there are alternative sources, which will cost the least to use in the long run? Getting the right answers is important (1).

The over-all cost of water will depend on many factors of which the following are most important:

1. Cost of getting the water into the plant by:
   (a) *purchase from an established distributing agency, such as a city water* department,
   (b) independent development of a surface or ground water supply.
2. Cost of primary treatment for general use by:
   (a) clarification,
   (b) filtration,
   (c) softening,
   (d) special treatment to remove iron, manganese, sulfide.
3. Cost of secondary conditioning for specific use in:
   (a) generation of steam for power or process,
   (b) cooling,
   (c) direct use in process.
4. Cost of maintenance and replacement of lines and equipment damaged by water through:
   (a) corrosion and cracking of metallic materials of construction,
   (b) chemical and biochemical attack on wood in cooling towers,
   (c) deposits of scale, sludge, or slime.
5. Cost of loss in production due to:
   (a) unscheduled outages of equipment,
   (b) reduction in flow in lines,
   (c) decrease in heat transfer.

6. Cost of damage to product by water in process operations, such as:
   (a) staining by corrosion products,
   (b) uneven dyeing of fabrics washed in water not adequately softened,
   (c) poor adhesion of finishes on steel due to dissolved solids dried out on metal surface.
7. Cost of treatment and/or disposal of contaminated effluent.

These component costs are so mutually dependent that no simple choice is usually evident. However, an engineering study of the entire projected use of water within the plant and of the optimum way to prepare the water for the different uses may well save more dollars during each year of subsequent operation than the entire cost of the original study.

Procurement of water may continue to be important to a plant throughout its operating life. Where ground water is the most available source, vigorous industrial expansion in a limited area tends to cause withdrawal of water from wells more rapidly than they are recharged by percolation along the water-bearing formation. The situation may become critical, as it did at Louisville, Kentucky (39), and at Texas City, Texas (29), during World War II.

Even though the underground aquifer is capable of supplying more water than is withdrawn, it tends to become progressively more plugged with finely divided particles of solid, so that less and less water can be pumped from a well. Chemical cleaning to dissolve or disperse the fines in the vicinity of the well may be essential to continued operation of the plant (15).

A source of water originally satisfactory for industrial use sometimes becomes so contaminated that it can no longer be used. For example, withdrawal at too great a rate from wells near the coast has resulted in the intrusion of sea water (26). A similar difficulty can occur when sea water backs up into the estuary of a river during a period of low flow (31). Inland surface supplies are always subject to changes in the character and amount of contamination as a result of industrial growth and the development of new processes in existing plants.

An important and relatively new development in procurement of water for industry is the use of the effluent from a municipal sewage disposal plant (41). Since 1942, the Sparrows Point Plant of Bethlehem Steel Company has used treated effluent from the city of Baltimore (43). In 1947, the amount that could be withdrawn for this purpose was increased to 100 million gallons per day. Use of such water is restricted to cooling operations and there is no interconnection with the sanitary water system.

Primary Treatment

What should be done to a water to prepare it for general use in a plant depends both on the substances carried by the water in suspension and solution and on the major uses to which the water will be put. Those steps in treatment that frequently are applied to all or most of a plant water are generally referred to as primary treatment; different types of secondary conditioning may then be necessary for specific uses, such as generation of steam, cooling, or processing of materials. Where a plant requires water of progressively higher quality for different purposes, successive stages of treatment may be designed.

The operations considered here as primary treatment are: clarification, filtration,

and softening, which have been discussed in considerable detail in many books and technical papers (6,10,19,23,30), together with the removal of iron, manganese, and sulfide, particularly troublesome constituents of some water supplies. For clarification and filtration, see pp. 955–58. See also *Sedimentation.*

SOFTENING

"Hard" water traditionally is water from which an insoluble soap precipitates when a soluble sodium soap is added. The precipitate, in general, is a mixture of calcium and magnesium soaps. Hence, *hardness* in water is commonly considered to mean the total concentration of calcium and magnesium ions (4). These are important not only with respect to washing operations in industry, but also the deposition of scale in boilers, condensers, and other heat exchangers. Hardness has commonly been expressed in terms of the equivalent amount of calcium carbonate in grains per gallon (g.p.g.). One grain per gallon equals 17.1 parts per million (p.p.m.). Chemical equivalents per million (e.p.m.) has been recommended as the fundamental unit for reporting hardness (3); since the equivalent weight of calcium carbonate is 50, hardness in e.p.m. is numerically $\frac{1}{50}$ of hardness in p.p.m. and $\frac{17.1}{50}$ or approximately $\frac{1}{3}$ of hardness in g.p.g.

Boiling a hard bicarbonate water drives off carbon dioxide, with resultant precipitation of part of the hardness. The term *temporary* or *carbonate hardness* accordingly has been used to describe that portion of the total hardness equivalent to the bicarbonate content of a water. Any remaining hardness has been known as the *permanent* or *noncarbonate hardness.*

The amount of a standard soap solution required to produce a stable lather when shaken with a sample of water was the measure of total hardness most commonly used for more than a century after it was described by Clark in 1841. Since 1950, the soap test (3) has been supplanted by the more precise and much quicker titration developed by Schwarzenbach (50). This depends on the change in color of an indicator sensitive to magnesium ion when calcium and magnesium ions have been sequestered in a soluble complex by a salt of ethylenediaminetetraacetic acid. By using another indicator sensitive to calcium ion, the concentration of the latter may be determined. Magnesium may then be calculated by difference. See *Sequestering agents.*

The "softening" of water for industrial use is accomplished by one or more of four major techniques: evaporation, precipitation, ion exchange, and sequestration.

Evaporation has been used to produce substantially pure water for make-up to high-pressure boilers or for industrial processes in which even small amounts of dissolved salts would be objectionable. Single-effect bent-tube evaporators are commonly employed in power plants (see also Vol. **5**, p. 937). Multiple-effect evaporators have been used to supply pure water for special purposes in industry. Condensate from a steam power plant or from a process using steam for heating also is water softened by evaporation. During World War II, vapor recompression evaporators were used by the Armed Services to produce all water for human use from sea water on islands lacking an adequate supply for large numbers of men (5). The classic worldwide example of water made soft by evaporation is afforded by rain.

Since an evaporator is a boiler, although operating at a relatively low pressure and temperature, it may require primary treatment of its feed water or internal chemical conditioning to minimize the difficulties subsequently described (see p. 937).

Precipitation of calcium and magnesium ions is accomplished most economically by the use of lime to remove the carbonate hardness:

$$Ca(HCO_3)_2 + Ca(OH)_2 \longrightarrow 2\,CaCO_3 + 2\,H_2O$$

$$Mg(HCO_3)_2 + 2\,Ca(OH)_2 \longrightarrow 2\,CaCO_3 + Mg(OH)_2 + 2\,H_2O$$

Soda ash is also used if the chemical balance of the raw water has a significant amount of noncarbonate hardness:

$$CaSO_4 + Na_2CO_3 \longrightarrow CaCO_3 + Na_2SO_4$$

$$MgCl_2 + Ca(OH)_2 + Na_2CO_3 \longrightarrow Mg(OH)_2 + CaCO_3 + 2\,NaCl$$

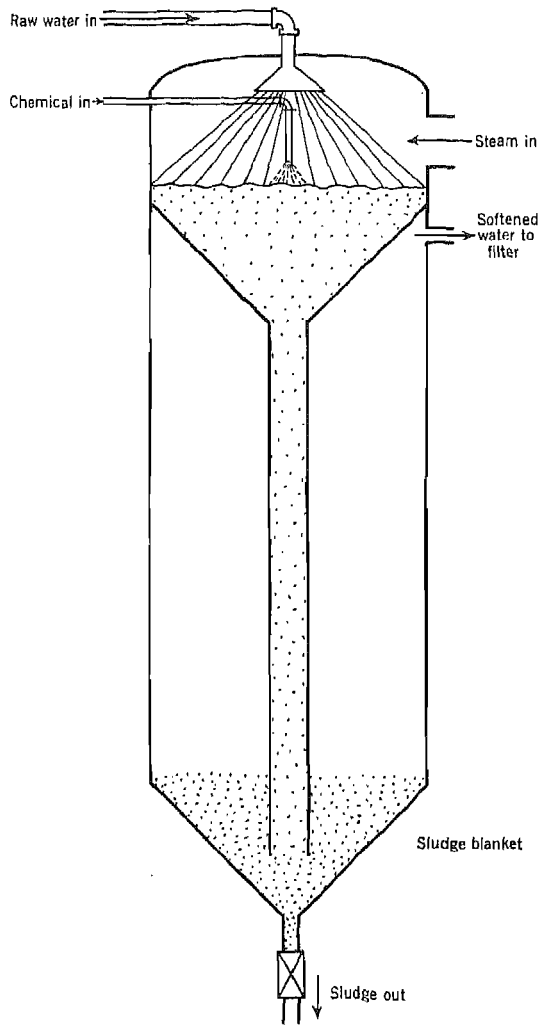


Fig. 1. Hot-process lime-soda softener (upflow type with sludge blanket).

Equilibrium calculations have been represented in complex graphs (9). A practical problem is posed, however, by the fact that precipitation, particularly of calcium carbonate, tends to be incomplete. Accordingly, quantities of lime and soda ash in

excess of those theoretically required for a particular water are actually used. The optimum excess to leave the lowest residual hardness is best determined in practice.

Softening by precipitation becomes more complete with increase in temperature. A "cold-process" softener operating at ordinary temperatures may leave 0.3–0.5 e.p.m. of hardness while the effluent from a "hot-process" unit operated under 3–5 p.s.i. steam pressure at 220–225°F. will show only 0.15–0.2 e.p.m. Relief of supersaturation at lower temperatures is also improved somewhat by retaining the water in the softener for a longer time. Recirculation of previously precipitated sludge to form a blanket through which the newly treated water passes is more practical in most cases than merely allowing a long time of reaction. A cross section through a softener of the sludge-blanket type is shown in Figure 1.

The hot lime-soda system functions not only as a softener but as a means of removing silica. Dissolved silica is adsorbed or reacts at the surface of each precipitated particle of magnesium hydroxide. To increase the amount of surface capable of removing silica from solution, magnesium-containing dolomitic lime is used instead of high-calcium lime. Alternatively, magnesium oxide prepared in a manner to produce an extended and readily hydrated surface may be added to the softener. Only 1–2 p.p.m. of SiO_2 (30) or even less may be left in the effluent.

In an effort to reduce the residual hardness from a hot-process softener, a separate second stage utilizing phosphate to precipitate calcium was sometimes employed. The effluent tended, however, to remain supersaturated with respect to calcium phosphate and to deposit this excess in the piping following the softener. Continuous controlled addition of acid to the water leaving the softener was usually necessary to prevent serious reduction in the capacity of the lines. The phosphate softener was rendered obsolete by the development of synthetic ion-exchange resins stable in the hot water from the lime-soda softener.

Known as the hot lime–zeolite system, the combination of precipitation and ion exchange provides nearly complete removal both of silica in the precipitation step and of hardness in the ion-exchange step. Residual values of 1–2 p.p.m. of SiO_2 and 2 p.p.m. of hardness as $CaCO_3$ are obtainable.

Filtration is generally desirable following a lime-soda softener. Sand has been used to handle the effluent from a cold-process unit, but the hot, alkaline water from a unit operated at higher temperatures dissolves silica from the sand. Where the water from a hot-process softener is to be employed as boiler feed water, as is frequently the case, the filter bed is accordingly constructed of a nonsiliceous material. Anthracite has been widely used for this purpose.

Ion Exchange. Softening by ion exchange (*q.v.*) is widely used. The natural and synthetic inorganic zeolites once employed for this purpose have been largely displaced by synthetic organic resins. In the solid particle of exchange material, charged with sodium ions by contact with a solution of ordinary salt, sodium ions are replaced by calcium and magnesium ions. When the ion-exchange material has absorbed all it can hold, it can be regenerated by means of the salt solution. The cycle of softening and regeneration can be repeated indefinitely if fouling with organic slimes, oxidized iron or manganese, silt, or precipitates from prior lime-soda softening is obviated.

When a hard, bicarbonate water is softened by ion exchange on the sodium cycle, the result is a dilute solution of sodium bicarbonate. As this is fed to a boiler, carbon dioxide passes into the steam and caustic soda accumulates in the boiler water:

$$2\ NaHCO_3 \longrightarrow Na_2CO_3 + H_2O + CO_2$$
$$Na_2CO_3 + H_2O \longrightarrow 2\ NaOH + CO_2$$

To obviate undesirable effects of this decomposition in the boiler, acid may be fed to the effluent from the exchanger, and the water then run down a baffled wooden tower against a rising stream of air which scrubs out the carbon dioxide released by the acid. Careful control obviously must be maintained to avoid feeding acid at a rate that will cause an excess of acid to be present in the water leaving the bottom of the decarbonator.

An alternative method of using acid to remove carbon dioxide is to charge an ion exchanger with hydrogen ions. When water is then passed through the bed of this exchange material, it comes out as a mixture of acids:

$$2\ NaHCO_3 + H_2Z \longrightarrow 2\ H_2O + 2\ CO_2 + Na_2Z$$
$$Ca(HCO_3)_2 + H_2Z \longrightarrow 2\ H_2O + 2\ CO_2 + CaZ$$
$$2\ NaCl + H_2Z \longrightarrow 2\ HCl + Na_2Z$$
$$MgSO_4 + H_2Z \longrightarrow H_2SO_4 + MgZ$$

The content of strong acids, such as hydrochloric and sulfuric, in this stream from the hydrogen exchanger can then be balanced against the content of bicarbonate in the stream from a parallel sodium exchanger so that the blended streams will lose substantially all of their carbon dioxide in a decarbonator. An advantage of this procedure over simple neutralization by added acid is the reduction effected in the content of dissolved solids.

Whether the acid for neutralization is used directly or as the regenerant for a hydrogen-cycle exchanger in a split-stream operation, the effluent from the bottom of the decarbonator will be corrosive because it is saturated with oxygen and because the pH must be low in order to allow carbon dioxide to be removed as completely as possible, preferably down to about 5 p.p.m. Corrosion-resistant piping, such as stainless steel or plastic, accordingly must be used to carry the water until specific steps are taken to reduce its corrosivity.

An alternative system of ion exchange makes possible both the softening and dealkalization of water without the use of acid. It requires the combined use of both cation-exchange resin and anion-exchange resin, each of which is regenerated with ordinary salt. Bicarbonate ion is replaced with chloride ion, while calcium and magnesium ions are replaced by sodium ion.

By employing the two types of resins either in series or in a mixed bed and regenerating the cation exchanger with acid and the anion exchanger with caustic soda, substantially complete removal of dissolved salts can be obtained. Water so pure that it exhibits a specific resistance of 10 million ohms or more can be prepared by this process of *deionization* or *demineralization*. Of particular importance with respect to feed water for high-pressure boilers is the ability to remove silica down to a residual of only 0.01–0.02 p.p.m. of SiO_2.

Dialysis. Various efforts have been made to remove dissolved solids from water by electrodialysis in a series of cells separated from each other by permeable membranes. Since cations and anions tend to migrate in opposite directions to the electrodes in the end cells, water of low solids content can be withdrawn after a while from the middle of the system. Both technical difficulties and cost have stood in the way of industrial purification of water by electrodialysis. Even the use of thin sheets

of ion-exchange resin as the membranes (17) seems unlikely to overcome the basic fact that both investment in plant and operating costs must be high. See also *Dialysis (electrodialysis)*.

Sequestration is applied frequently not only as primary treatment but also as secondary conditioning following primary softening by other means. Sequestration of calcium and magnesium ions in a soluble complex so very stable that addition of soap produced no precipitate was first accomplished in 1932, using the sodium phosphate glass known as Graham's salt or sodium "hexametaphosphate" (see Vol. **10,** p. 418) (44). Modified sodium phosphate glasses containing from 67 down to 63% P_2O_5, as well as crystalline sodium triphosphate(tripolyphosphate), $Na_5P_3O_{10}$, have since been used widely in industrial and domestic washing operations, not only in conjunction with soap but also with synthetic detergents. The phosphates disperse soil as well as sequestering all hardness, both that initially present in the water and that brought in on the objects being washed.

Organic sequestering or *chelating* agents, such as the sodium salts of ethylenediaminetetraacetic acid form a highly stable complex with many metal ions, including iron as well as calcium and magnesium. In spite of their relatively high cost, these sequestering agents (*q.v.*) have found a number of special industrial applications, such as the control of hardness and iron in textile dye baths operated at or near the boiling point.

For any industrial plant and its available source or sources of water, two questions naturally occur. (1) Will softening be essential or desirable? (2) If so, what method of softening should be chosen? The answer to the first question may be obvious because of past experience; an engineering analysis of the situation usually will be necessary, however, to provide an answer to the second which will be sound from a technical and hence from an economic viewpoint. A great deal of money has been ill spent on softening plants poorly adapted to specific needs.

REMOVAL OF IRON AND MANGANESE

Dissolved iron and, less frequently, manganese may prove to be a serious problem in the industrial use of water. After exposure to the air has oxidized ferrous or manganous ion, colored precipitates of hydrous ferric oxide or manganese dioxide are formed which not only tend to plug lines and foul equipment but also stain products with which they may come in contact.

Aeration followed by settling and filtration is used to remove iron where no other primary treatment is required. Addition of chlorine may be desirable in some cases to speed the oxidation of the iron to completion. Softening by precipitation normally takes out substantially all of the dissolved iron. Softening by ion exchange will remove dissolved iron in the ferrous state and this can be displaced from the resin during regeneration. However, if oxidation of the iron has commenced due to contact of the water with air prior to the ion-exchange unit, the resin will tend to become coated with hydrous ferric oxide and thereby lose capacity.

Manganese is more difficult to remove than iron. Chlorination beyond the breakpoint, which signifies that everything in the water has been completely oxidized, is necessary (20) (see p. 960). To minimize plugging of the final sand filter, it may be desirable to pass the water first through a contact filter of anthracite and then through a settling basin.

Removal of iron or manganese from well water is actually unnecessary in many

cases, since a few parts per million of either may be adequately controlled by the glassy sodium phosphates previously mentioned in connection with sequestration (46). From 1 to 4 parts of the complex phosphate are required for each part of dissolved iron. Somewhat greater amounts may be necessary to control manganese. In either case, it is essential that the phosphate be present in the water before the iron or manganese is subjected to contact with air or any other oxidizing agent, such as chlorine. Where the glassy sodium phosphates are not sufficiently stable, as in the hot textile dye baths previously mentioned, the more expensive salts of ethylenediaminetetraacetic acid provide effective control of iron or other metal ions.

REMOVAL OF SULFIDE

Some well waters carry dissolved sulfides which accelerate corrosion of steel equipment in addition to producing a nuisance as far as taste and odor are concerned. Sulfide-contaminated water also results from the mining of sulfur by the Frasch process. In this industry hydrogen sulfide is removed from the water before it is reheated and recirculated underground to melt more sulfur. This is done by allowing the contaminated water to cascade down over wooden towers countercurrent to a rising stream of air. Where substantially complete elimination of sulfide is necessary, the pH of the water should be reduced to 4–5 before it is subjected to forced-draft aeration. As a final step, chlorine is used in an amount sufficient to oxidize the residual sulfide (31).

VACUUM DEAERATION

Dissolved oxygen accelerates corrosion by water. Whenever a well water substantially devoid of oxygen is aerated to remove carbon dioxide, hydrogen sulfide, or iron, or is heavily chlorinated to remove organic matter or manganese, the resulting water is very corrosive to steel. Since all surface water supplies tend to approach saturation with respect to oxygen, they also are inherently more corrosive than they would be if the oxygen were removed.

Deaeration by heating to or even above the atmospheric boiling point is practiced in power plants where the feed water must be heated anyway. For mechanical deaeration of water at ordinary temperatures, it is necessary to use vacuum to remove the dissolved gases. To provide a large surface for transfer of these gases to the vapor phase, the water is sprayed into the shell of the deaerator, which is maintained under low pressure by a pump capable of evacuating the gases more rapidly than they are released (31).

Secondary Conditioning

Even after an industrial water supply has been clarified and softened, it may still cause trouble when used as feed water for a boiler or as cooling or process water. For each specific application, some form of secondary conditioning may be necessary to achieve the optimum of lowest over-all costs.

Chemical conditioning of water requires equipment for feeding, systematic testing to maintain proper concentrations in the system, and technical supervision, in addition to the cost of the chemicals themselves. There is naturally a strong interest in achieving desired results by more simple means. As a result, there has been a continuing succession of devices since 1865 purporting to prevent scale and corrosion by nonchemical means. Alleged to produce the desired results by electrical, magnetic,

catalytic, radioactive, or supersonic forces, the actual performance of these "gadgets" on industrial water has been poor (42).

While cathodic protection has produced real benefits in the protection of buried pipe lines from corrosion by ground water and of ships' hulls from corrosion by sea water, it has not proved generally practical to apply sacrificial anodes to the protection of the internal surfaces of water distribution systems or the complex equipment through which water passes.

WATER FOR GENERATION OF STEAM

The Industrial Revolution was based upon the use of water as a means of converting into mechanical work the energy released by a chemical reaction between coal and air. Even though fossil fuels may be replaced by nuclear energy, the production of steam from water still seems likely to retain, at least through the 20th century, its important place in the generation of power. Equally certain is the continued use of steam for process heating.

When water is converted into steam (*q.v.*) in a boiler, the substances initially present in solution in the water have only three places to go: (*1*) They may concentrate in the water remaining in the boiler as dissolved solids, which must be removed intermittently or continuously by blow-down to waste. (*2*) They may precipitate from solution to form either deposits of boiler scale on the surfaces where boiling takes place or particles of suspended solids which may collect in some portion of the boiler as sludge. (*3*) They may be picked up by the steam leaving the boiler and be transported as carry-over to the superheater and the equipment ultimately receiving the steam. At the same time, the water is continuously reacting with the steel, so that corrosion must be added to the list of problems to be faced in the conditioning of water for generation of steam.

The purpose of boiler water conditioning is to keep the over-all cost of generating steam to a minimum by obviating failures of equipment and by reducing the amount of maintenance work required. To this end it is essential to control corrosion, to prevent scale, and to maintain the purity of the steam.

Control of Corrosion (*q.v.*). While water is being converted into steam in the boiler and then heated to a still higher temperature in the superheater, the confining surfaces of steel are reacting with the water or steam to produce iron oxide and hydrogen:

$$3\,Fe + 4\,H_2O \longrightarrow Fe_3O_4 + 8\,H$$

Were it not for the fact that the reaction can be almost completely stifled by the first iron oxide developed on the metal surface, boilers could not be made of ordinary low-carbon steel. Progressive increases in the temperature of superheated steam have only been made possible, as a matter of fact, by the application of alloys capable of producing a more protective coating. It has truly been said that a boiler, from the chemical viewpoint, is a thin film of iron oxide supported by steel.

To produce and maintain the most protective oxide film is one of the primary objectives of the chemical conditioning of boiler water, which was first reduced to a scientific basis during the period from 1922 to 1926 (12). Two things must be done: (*1*) dissolved oxygen must be substantially eliminated from the feedwater and (*2*) the concentration of free sodium hydroxide in the boiler water must be maintained in a favorable range.

Dissolved oxygen is most economically removed from feed water by mechanical deaeration. An open heater of the simple spray or tray type, although nominally guaranteed only to reduce oxygen below 0.03 ml./liter(0.043 p.p.m.), often will leave only 0.01 ml./liter(0.014 p.p.m.) or less. Even lower figures, down to 0.005 ml./liter (0.007 p.p.m.), are guaranteed for more elaborately designed two-stage deaerators. Methods for determining residual dissolved oxygen down to this low level are available (2).

As a second line of defense, an oxygen scavenger is frequently added, preferably to the storage space of the heater. Sodium sulfite, widely used for this purpose, ends up as dissolved sulfate in the boiler water:

$$2\,Na_2SO_3 + O_2 \longrightarrow 2\,Na_2SO_4$$

and may also undergo reduction to sulfide at hot spots, but it is inexpensive and effective. Its rate of reaction with oxygen in unheated water may be accelerated by catalysis, using very low concentrations of several metal ions. About 0.002 p.p.m. of cobalt ion is usually employed where protection of cold-water lines and equipment is important. No catalyst is needed at the higher temperatures following mechanical deaeration, where sulfite is usually employed.

A small excess of sulfite is maintained in a boiler water to serve as an indication that dissolved oxygen is being completely eliminated. This may range from as little as 1 p.p.m. in central-station operation to 60 p.p.m. or more in low-pressure industrial boilers.

Following the large-scale production of hydrazine as a rocket fuel in Germany during World War II, this substance was also applied as a chemical scavenger for dissolved oxygen. Its advantage of not adding dissolved salts to the boiler water while combining with oxygen according to the reaction:

$$N_2H_4 + O_2 \longrightarrow N_2 + 2\,H_2O$$

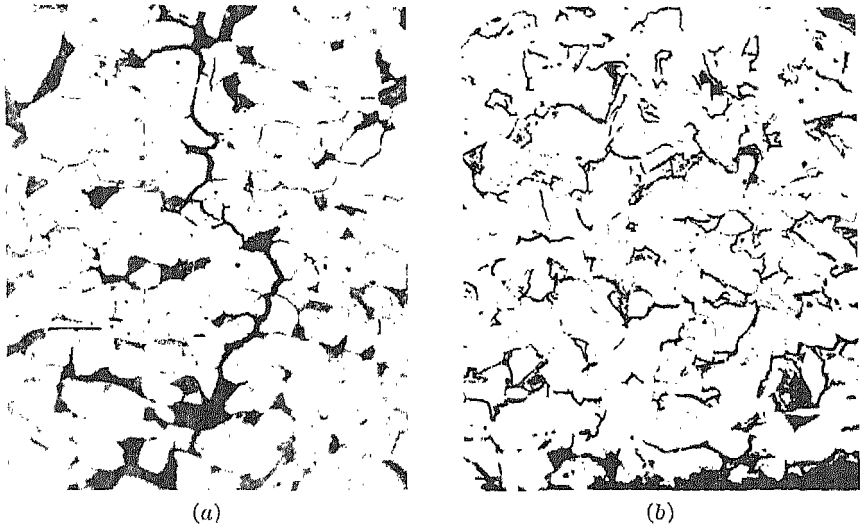
has been offset, however, by its high cost and its slow rate of reaction with dissolved oxygen at the temperatures up to about 220 °F. and pH values up to about 9 characteristic of many boiler feed waters. In high-pressure boilers, hydrazine decomposes so rapidly to ammonia that only a very low residual concentration of 0.005–0.01 p.p.m. is maintained.

The second requirement of maintaining the concentration of free sodium hydroxide in the boiler water in a favorable range involves judgment and practical experience (27). Both pure water and strong caustic solutions attack steel at boiler temperatures more rapidly than water containing a few hundred parts per million of sodium hydroxide. However, the concentration of dissolved substances may vary a great deal from point to point within a boiler. If the mass of water in a drum contains 300 p.p.m. of sodium hydroxide, the concentrating film on the surface of a tube producing steam at a high rate may contain so much caustic that the metal will be attacked (33). Tubes that are horizontal or only slightly inclined are more likely to be damaged because steam trapped along the top of the tube tends to cause overheating of the steel, with correspondingly rapid attack by the concentrating film (28).

It is necessary to judge the optimum concentration of sodium hydroxide for a boiler initially in terms which include its design and how much steam it is required to deliver, then finally by its performance. Since the concentration of sodium hydroxide affects also the behavior of the sludge and the purity of the steam, no simple rules will cover all cases. Most boiler waters under chemical control will have limits for the

concentration of sodium hydroxide set somewhere in the range from 25 to 500 p.p.m. of NaOH.

When the drums of power boilers were fabricated with riveted seams, a number of serious explosions occurred because cracking from rivet hole to rivet hole along a seam was induced by the combined effects of stress in the steel and accumulation of a concentrated solution of caustic between the plates. The cracking resulted from intergranular corrosion, such as that illustrated in Figure 2, which progressively weakened the steel until it would fail in an apparently brittle manner. This caused the type of failure to become known as *caustic embrittlement* (36). Since boiler drums are now almost universally constructed with welded seams, the only locality where caustic embrittlement is still likely to occur is in the end of a tube, where rolling into a header or a drum may provide the necessary combined factors of stress and caustic concentration. Cracking of tube ends is, however, rare.



(*a*) (*b*)

Fig. 2. Microstructures of steel (×300, nital etch): (*a*) Caustic embrittlement of a tube end in low-pressure boiler (note normal microstructure with no evidence of decarburization); (*b*) Hydrogen embrittlement of a wall tube in a 1400-p.s.i. boiler (note many ruptured grain boundaries and general decarburization).

The most effective chemical means of minimizing caustic embrittlement is to maintain sodium nitrate in the boiler water in a ratio of 0.4 part of sodium nitrate for each part of sodium hydroxide (8,34).

Intergranular damage in steel is also produced in relatively rare cases by hydrogen resulting from local reaction of the steel with the boiler water. At least part of the hydrogen enters the metal in atomic form. As it diffuses through the steel, it reduces carbides at grain boundaries, forming methane which cannot escape because of the relatively large size of its molecule. The effect on the microstructure is indicated in Figure 2. When enough grain boundaries have been ruptured, cracking in an apparently brittle manner occurs. This type of failure, which characteristically shows some evidence of decarburization, is known as *hydrogen embrittlement*. Stress is an accelerating factor, as is moderate overheating. Free caustic is not necessary, how-

ever, as hydrogen embrittlement has been observed in boilers from which all alkaline materials were carefully excluded (27).

Corrosion may occur not only in the boiler but also after the steam has condensed again to water. Where a heating system is not operated continuously under pressure, oxygen in the air drawn back into the lines or equipment when the steam is turned off accelerates the attack of the condensate on the metals in the system. Moreover, when a water containing bicarbonate is fed to a boiler, the steam will carry some carbon dioxide and the condensate accordingly will tend to be acid. Return lines through which such condensate is flowing may be eaten away in a few months.

To neutralize the carbon dioxide in steam, volatile alkalies such as ammonia, cyclohexylamine, or morpholine are fed to maintain the pH value of the condensate at a level sufficiently high to minimize corrosion (25). Where condensate is not returned to the boiler and where inleakage of oxygen is a factor, filming amines such as *n*-octadecylamine are used as inhibitors of corrosion (45,49). This type of substance affords protection by forming an adsorbed film on the metal.

Damage by corrosion while a boiler is out of service probably exceeds that occurring during use. To protect equipment during stand-by, it should either be kept thoroughly dry or should be completely filled with water containing sodium hydroxide and sodium sulfite (13).

Prevention of Scale. The earliest boilers used to blow up all too frequently because the shell and the fire tubes through which heat was transferred from the furnace to the water became covered with a thick "fur" or scale. This was usually calcium sulfate or calcium carbonate, depending on whether the water had flowed through gypsum or through limestone on the way to the point of use. Less frequently, scales of calcium silicate were encountered. Through the first quarter of the 20th century, hard scales of calcium compounds were a common cause of failure of boiler tubes by overheating and blistering.

Originally, it was assumed that the scale resulted from the baking-on of separate particles of solid which had precipitated in the boiler water as it was concentrated, then settled on the boiler surfaces. By 1925 it was known that the scale actually crystallized from solution directly onto the heat-transfer surface (11). This led to the system, later adopted throughout the world, of maintaining at all times in the boiler water a small but sufficient excess of phosphate ion so that all calcium ion entering with the feed water would be precipitated as a loose sludge of calcium phosphate rather than as a hard scale. The calcium phosphate formed is generally hydroxylapatite, as indicated by the equation:

$$10\ CaCl_2 + 6\ Na_3PO_4 + 2\ NaOH \longrightarrow \underset{\text{hydroxylapatite}}{Ca_{10}(PO_4)_6(OH)_2} + 20\ NaCl$$

Magnesium ion, on the other hand, is preferably precipitated as magnesium silicate, rather than as magnesium phosphate or magnesium hydroxide. The magnesium silicate consistently formed in boiler sludge is the mineral serpentine, as indicated by the equation:

$$3\ MgSO_4 + 2\ Na_2SiO_3 + 2\ NaOH + H_2O \longrightarrow \underset{\text{serpentine}}{3\ MgO.2\ SiO_2.2\ H_2O} + 3\ Na_2SO_4$$

Although sludge does not usually accumulate to a significant extent in the tubes where water is boiling vigorously, it may tend to stick to the surfaces immediately following the mixing of incoming feed water with the boiler water. In an attempt to

minimize such deposits, various organic materials, including tannins, derivatives of lignin, and extracts from seaweed have been employed as *dispersives*, but with only partial success. While in many cases the organic additives do reduce the tendency of sludge to adhere to surfaces which are relatively cool, they may add to the amount of deposit on some "hot spot" receiving heat at an exceptionally high rate (18). In extreme cases, elemental carbon resulting from decomposition of an organic dispersive has formed 15–20% of a deposit which was chiefly complex sodium aluminum silicate.

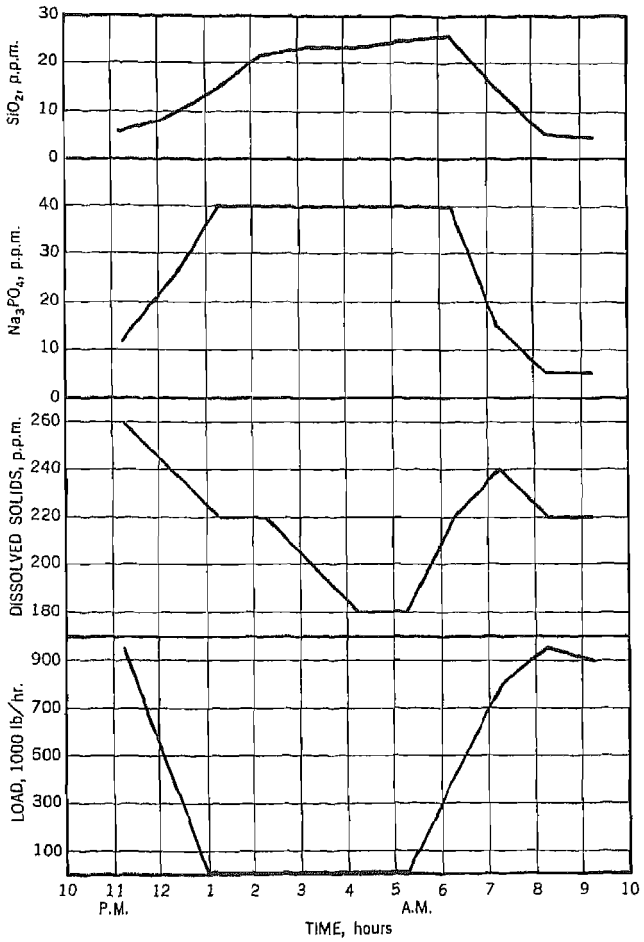


Fig. 3. Hide-out of silica and phosphate in a high-pressure high-capacity boiler.

The *complex silicates*, of which analcite, $NaAlSi_2O_6.H_2O$, occurs most frequently in boilers, may be deposited when the boiler water is being concentrated locally to an extreme degree (33). Generation of steam bubbles at a tube surface tends to leave next to the surface a film of water in which dissolved solids are concentrated. Unless this film is continuously and sufficiently rinsed away by the turbulent flow of boiler water through the tube, even such soluble constituents as sodium sulfate and sodium phosphate may be laid down as well as the complex silicates.

The soluble sodium sulfate, phosphate, and silicate deposited locally from the

concentrating film during periods of high load on a boiler may be redissolved when the rate of steam generation is reduced. The term "hide-out" has been applied to this disappearance and reappearance of soluble constituents, an example of which is represented graphically in Figure 3. As the boiler load is decreased, the amount of dissolved solids decreases, because feed water enters the boiler to replace steam, thus diluting the boiler water. In contrast, the amounts of silica and phosphate increase, showing that deposits of water-soluble solids are dissolving. When the boiler is returned to service, *the dissolved solids increase as steam is produced, but silica and* phosphate again "hide out." Complex silicates redissolve very slowly in comparison to the simple sodium salts.

In addition to the control of sodium hydroxide in the boiler water mentioned previously, chemical control of phosphate is generally practiced. The limiting values recommended may range from not more than 5 p.p.m. of PO_4 radical in a boiler generating 500,000 lb. of steam per hour at 1,400 p.s.i. in a central station to 100 p.p.m. in small boilers at relatively low pressures.

Control of silica is varied to meet the needs. It may be carried higher than the phosphate for the purpose of minimizing sludge accumulation at pressures up to more than 600 p.s.i., but is excluded from high-pressure boilers as completely as possible for the reason set forth in the following section.

Steam Purity. Steam containing no more than 0.5 p.p.m. of solids from the boiler water is generally considered desirable in power plants to minimize deposition of the solids in the turbine. Mechanical entrainment of boiler water as foam or as a mist in the steam leaving the boiler accordingly must be kept to a minimum. Mechanical separators comprising either small cyclones or one or more baffles to reverse the direction of steam flow are generally employed. Steam washers in which the steam flows countercurrent to entering pure feed water are also used. Every effort is made to exclude foam-producing contaminants from the feed water. Specific substances that act to cause rapid coalescence of bubbles under boiler conditions are added as antifoams. See Vol. 6, p. 776. Electrical conductivity of the condensate is measured to guard against contamination by inleakage of condenser cooling water.

In spite of all such precautions, deposition of silica may occur in turbines using steam at pressures of 1200–1400 p.s.i. and above. This is due to the fact that steam at high pressure and temperature can actually carry in solution in the vapor phase a small amount of silica; as the pressure and temperature decrease progressively through the turbine, the solubility also decreases and the silica is deposited. In high-pressure central stations, the problem of deposition of silica on turbine blades is minimized by keeping silica out of the boiler water as completely as possible.

COOLING WATER

The need for removing heat from some operation is almost universal throughout industry. In the power plant, steam leaving the turbine must be condensed, as must the vapors from the fractionating columns in the oil refinery, the distillery, or the plant making organic chemicals. Metallurgical furnaces require cooling, as do diesel and gas engines, welding tips, reaction vessels, air-conditioning units, to mention only a few. Water is the universal coolant.

Where water is plentiful and costs little, it is run continuously through the equipment to be cooled. If the water leaving such a "once-through" system picks up enough *heat to raise its temperature 10°F., then 100 lb. of water would be required to dissipate*

1000 B.t.u. Shortage of water or the cost of procuring large quantities has led to the widespread adoption of cooling towers in which the evaporation of only 1 lb. of water will remove the same amount of heat, the rest of the water being recirculated.

Since a cooling tower evaporates water, any dissolved solids must concentrate in the system, as in a boiler. Blow-down of some water is therefore essential. This may be regulated manually on the basis of chemical tests or either manually or automatically on the basis of electrical conductivity.

Treatment of a specific water to produce optimum results in cooling differs from treatment required by the same water as feed for a boiler. While removal of suspended silt may be necessary, there is frequently no need to soften cooling water. A hard, bicarbonate water will tend to lay down a scale on any hot metal surface, but this can be prevented in most cases at temperatures up to the atmospheric boiling point by adding to the water only about 2 p.p.m. of a complex phosphate which inhibits crystallization of calcium carbonate (48). Sulfuric acid may also be employed under careful control to neutralize part of the alkalinity.

Cooling water almost always corrodes steel and may attack other metals in equipment through which it passes. In recirculating systems, this corrosion is commonly controlled by adding various inhibitors, such as a complex glassy phosphate, alone (47) or with a chromate (14). Because so much more water is discharged from a once-through system, chemical treatment beyond such rudimentary measures as adding lime to neutralize acidity may be uneconomical.

Much effort has been expended on attempts to control the composition of a water so that it would lay down a coating of calcium carbonate so thin as to have no appreciable effect on heat transfer yet so continuous and impervious that it would protect the metal surfaces in a distribution system and the equipment served by it. The Langelier index (16), which is numerically the difference between the actual pH of the water in a system and the pH at which that water would be saturated with respect to calcium carbonate, has been used to a considerable extent as a guide. A water with a slightly positive index, indicating some supersaturation with respect to calcium carbonate, is considered desirable. Difficulties have been encountered in practice because deposition of calcium carbonate tends to occur wherever the degree of supersaturation is increased, as in the piping following upward adjustment of pH or on heat-exchange surfaces. Moreover, the physical characteristics of the deposit may be modified adversely by various constituents of the water so that a good protective coating does not develop.

The moderate temperatures in many cooling systems encourage the growth of simple organisms such as algae and bacteria. The resulting slime may seriously impede heat transfer or interfere with flow of water. To control these organic growths, chlorine is commonly fed to the water. Bromine has been used to some extent in place of chlorine. Chlorinated organic compounds with biocidal properties, such as chlorophenates, have been employed where the water contained so much nonliving organic contamination that the amount of chlorine consumed was excessive.

Although the redwood used in cooling towers is particularly resistant to decay, it is subject to both chemical and biochemical damage. The more alkaline a water is, the greater the tendency to weaken the wood by extracting such constituents as lignin. Accordingly, a pH value of not more than 7 would be considered desirable (7). Chlorination should also be limited to the minimum program that will control slime.

Serious damage to wooden cooling towers, particularly to the portions, such as the

mist eliminators, that are moist but not covered by flowing water, has been caused by fungi. Treating the wood with fungicides either before a new tower is constructed or when attack by fungus is first noted or is feared appears to be the most practical procedure.

Chemical control of cooling water usually comprises a check on the hardness, the pH, the alkalinity, the inhibitor or inhibitors employed, and, in a recirculating system, the number of times the water has been concentrated.

WATER FOR PROCESS USE

In the process industries, water is not only used for the generation of steam power and for cooling, but it may also appear in varied roles in the process steps themselves (19). For example, water may be used to convey materials in suspension or in solution, to provide a medium for all types of chemical reaction, to help separate materials, or to become part of the product. Almost every process industry requires water in one operation or another. A few of the many possible examples are indicated below. In each process use, specific constituents naturally present or added to the water may cause trouble.

In the manufacture of pulp and paper, water is used to float the logs to the pulp mill. Jets of water under high pressure are sometimes used to strip off the bark. The wood is cooked with an aqueous solution under pressure to separate the cellulose fibers from the lignin and other constituents. In the pulping of wood by the sulfite process, the liquor is heated in an exchanger which scales up with calcium sulfite and sulfate. The cellulose is bleached by contact with aqueous solutions of oxidizing agents. Iron in the water results in undesirable color. The fibers are dispersed in water and transported to a screen to form paper. And finally, if the paper is coated, the coating materials are applied in the form of an aqueous dispersion.

Cotton, wool, and synthetic fibers all undergo repeated washing operations in which large quantities of water are used. Bleaching and dyeing steps likewise require water. Hardness, color, iron, and manganese all cause trouble.

A surface to be electroplated customarily is cleaned by means of water solutions first of alkali and then of acid. The desired metal is then plated onto it from another aqueous solution, after which it must be rinsed with water to remove all of the plating solution. High dissolved solids in the water used to make up the electroplating bath may impair the quality of the plating.

Before organic finishes can be applied to an auto, a refrigerator, or any other metal object, rust and grease must be removed, respectively, by pickling in an aqueous solution of acid, rinsing with water, washing in a strongly alkaline detergent solution, and rinsing again with water. An additional step of forming a phosphate coating on the cleaned steel surface also involves an aqueous solution. Carry-over of dissolved salts from the rinse water onto the cleaned steel surface can cause blistering of the finish.

To separate coarser particles of sand from clay, the crude clay is dispersed in water. After the sand has settled out, the dispersed clay is flocculated and recovered.

Spray residues comprising poisonous materials are removed from fruit by continuous washing and rinsing operations involving the use of considerable quantities of water.

In the bottling of beer and soft drinks, the product is chiefly water containing relatively small amounts of constituents producing characteristic flavor and color.

Water low in bicarbonate and high in calcium sulfate hardness has traditionally been desired by breweries.

Water that might be unobjectionable for use in one process may cause no end of trouble in another. A hard, bicarbonate water containing 2 p.p.m. of dissolved iron would be suitable for quenching coke but could not be tolerated in a dye bath or most other textile-processing operations. In the manufacture of photographic film, chlorine cannot be used as an algicide.

Chemical Control Methods

All chemical treatment of water depends upon adequate chemical control involving the measurement of a constituent, such as phosphate, or of a property, such as electrical conductivity. In addition, it is often desirable to know the identity of the actual substances in a deposit or a corrosion product. For this purpose, the polarizing microscope and x-ray diffraction equipment have been applied.

Methods for both chemical and instrumental analysis are continually being standardized and improved by the American Society for Testing Materials (19) and by the joint effort of the American Public Health Association and the American Water Works Association (35). In addition, simplified control methods are used by the various organizations offering consultation and technical service in the field of industrial water. Control methods for use in the conditioning of boiler water also are appended to Section VII of the Boiler Code of the American Society of Mechanical Engineers (37). See *Water (municipal)*.

Bibliography

(1) Anon., *Power*, **96**, No. 9, 71–118 (1952).
(2) A.S.T.M. D888, "Dissolved Oxygen in Industrial Water."
(3) A.S.T.M. D1126, "Hardness in Industrial Water."
(4) A.S.T.M. D1129, "Terms Relating to Industrial Water."
(5) Aultman, S. W., *J. Am. Water Works Assoc.*, **42**, 786–94 (1950). (Discussion by C. H. Spaulding, 795–96.)
(6) Babbitt, H. E., and Doland, J. J., *Water Supply Engineering*, McGraw-Hill, N.Y., 1949.
(7) Baechler, R. H., and Richards, C. A., *Trans. Am. Soc. Mech. Engrs.*, **73**, 1055–59 (1951).
(8) Berk, A. A., *Trans. Am. Soc. Mech. Engrs.*, **73**, 859–64 (1951).
(9) Caldwell, D. H., and Lawrence, W. B., *Ind. Eng. Chem.*, **45**, 535–48 (1953).
(10) Feller, E. W., *Power*, **91**, No. 12, 63–98 (1947).
(11) Hall, R. E., *Ind. Eng. Chem.*, **17**, 283–90 (1925).
(12) Hall, R. E., *et al.*, "A Physico-Chemical Study of Scale Formation and Boiler-Water Conditioning," *Min. Met. Invest., Carnegie Inst. Tech.*, Bull., **24** (1927).
(13) Highley, L., Jr., and Schnarrenberger, W. R., *Corrosion*, **8**, 171–77 (1952).
(14) Kahler, H. L., and Gaughan, P. J., *Ind. Eng. Chem.*, **44**, 1770–74 (1952).
(15) Kleber, J. P., *J. Am. Water Works Assoc.*, **42**, 481–84 (1950).
(16) Langelier, W. F., *J. Am. Water Works Assoc.*, **28**, 1500–21 (1936).
(17) Langelier, W. F., *J. Am. Water Works Assoc.*, **44**, 845–58 (1952).
(18) Liddell, R. W., and Bishop, L. C., *Proc. Midwest Power Conf.*, **13**, 263–74 (1951).
(19) *Manual on Industrial Water* (A.S.T.M. Spec. Pub. 148), 2nd ed., 1954.
(20) Mathews, E. R., *J. Am. Water Works Assoc.*, **39**, 680–86 (1947).
(21) Morris, W. S., and Peterson, S. F., *J. Am. Water Works Assoc.*, **37**, 569–76 (1945).
(22) National Assoc. Mfgrs. and Conserv. Found., *Water in Industry*, N.Y., 1950.
(23) Nordell, E., *Water Treatment for Industrial and Other Uses*, Reinhold, N.Y., 1951.
(24) Ohio River Valley Water Sanitation Commission, *Annual Reports*, 1948–49, et seq.

(25) "Panel Discussion on Corrosion and Deposits in Condensate and Feedwater Systems," *Proc. 14th Annual Water Conf., Eng. Soc. Western Pa.*, **1953**, 81–118.
(26) Parker, G. G., *J. Am. Water Works Assoc.*, **37**, 526–42 (1945).
(27) Partridge, E. P., *Consult. Eng.*, **2**, No. 8, 28–31, 68, 70, 72 (1953).
(28) Partridge, E. P., and Hall, R. E., *Trans. Am. Soc. Mech. Engrs.*, **61**, 597–622 (1939); added discussion, **62**, 711–17 (1940).
(29) Powell, S. T., *J. Am. Water Works Assoc.*, **40**, 8–23 (1948).
(30) Powell, S. T., *Water Conditioning for Industry*, McGraw-Hill, N.Y., 1954.
(31) Powell, S. T., and von Lossberg, L. G., *Chem. Eng. Progress*, **45**, 289–300 (1949).
(32) President's Water Resources Policy Commission, I. *A Water Policy for the American People*, U.S. Govt. Printing Office, Washington, D.C., 1950.
(33) Rivers, H. M., *Proc. 12th Annual Water Conf., Eng. Soc. Western Pa.*, **1951**, 131–45.
(34) Schroeder, W. C., and Berk, A. A., "Intercrystalline Cracking of Boiler Steel and Its Prevention," *U.S. Bur. Mines Bull.*, **443** (1941).
(35) *Standard Methods for the Examination of Water and Sewage*, Am. Pub. Health Assoc., N.Y., 1946.
(36) Straub, F. G., "Embrittlement in Boilers," *Univ. Ill., Eng. Expt. Sta. Bull.*, **216** (1930).
(37) *Suggested Rules for Care of Power Boilers*, Am. Soc. Mech. Engrs., N.Y., 1954, pp. 46–52.
(38) U.S. Dept. of Commerce, *Climatological Data, National Summary Annual 1952*, Vol. 3, No. 13.
(39) U.S. Geol. Survey, *J. Am. Water Works Assoc.*, **37**, 543–62 (1945).
(40) U.S. Geol. Survey, The Industrial Utility of Public Water Supplies in the United States, 1952: 1. States East of the Mississippi, Water Supply Paper 1299, 1954; 2. States West of the Mississippi, Water Supply Paper 1300, 1954.
(41) Veatch, N. T., *J. Am. Water Works Assoc.*, **40**, 1–7 (1948); *Sewage Works J.*, **20**, 3–14 (1948).
(42) Welder, B. Q., and Partridge, E. P., *Ind. Eng. Chem.*, **46**, 954–60 (1954).
(43) Wolman, A., *Sewage Works J.*, **20**, 15–23 (1948).
(44) U.S. Pat. Re. 19,719 (Oct. 8, 1935), R. E. Hall (to Hall Laboratories, Inc.). Reissue of **1,956,515**.
(45) U.S. Pat. Re. 23,614 (Jan. 13, 1953), W. L. Denman (to Dearbon Chemical Co.). Reissue of **2,400,543**.
(46) U.S. Pat. 2,304,850 (Dec. 15, 1942), O. Rice (to Hall Laboratories, Inc.).
(47) U.S. Pat. 2,337,856 (Dec. 28, 1943), O. Rice and G. B. Hatch (to Hall Laboratories, Inc.).
(48) U.S. Pat. 2,358,222 (Sept. 12, 1944), G. J. Fink and H. H. Richardson (to National Aluminate Corp.).
(49) U.S. Pat. 2,460,259 (Jan. 25, 1949), H. L. Kahler (to W. H. and L. D. Betz).
(50) U.S. Pats. 2,583,890; -891 (Jan. 29, 1952), G. Schwarzenbach (to Chemische Fabrik Uetikon, Switzerland).

EVERETT P. PARTRIDGE

MUNICIPAL WATER

Most large cities must depend upon surface sources for their supply while, in general, small communities obtain adequate quantities from springs or deep wells.

Municipal water is put to many and varied uses. In addition to that used for drinking, it is the source of all uses in the home, as well as in many small industries, such as laundries, and in restaurants, stores, and other small business establishments. Considerable quantities are used for minor irrigations, for sprinkling of lawns and gardens, etc., and in recent years there has been an increasing demand for water to carry away the heat in air conditioners. Added to this, the city or municipality needs considerable quantities in times of emergency for the fighting of fires. The demand varies from 50 to 300 gal. per capita per day, depending to some extent upon the population, being in general greater in larger communities than in small ones. In most cities, it is advisable to provide emergency equipment to pump or handle more water than the normal daily demand because of the possibility of emergencies such as extensive fires.

The water is generally distributed under pressure through underground mains and

service pipes from the mains to the individual user. Pressure is maintained either by pumps which deliver the water under pressure into the distribution system or by tanks, and reservoirs at sufficient elevation to provide the necessary static head. Where storage tanks are used, water is generally pumped into them intermittently, but the level is maintained between fixed points.

Delivery of water to individual homes through an underground distribution system is a rather recent development in our civilization which, however, has brought with it new and significant routes of spreading communicable diseases. In the early days of this practice, adequate treatment was not instituted and proper precautions were not taken to prevent pollution of the water supply. The result was many extensive water-borne epidemics that forced recognition of the need for standards of purity, methods of testing, and methods of purification. The U.S. Public Health Service has taken a leading part in this, and from time to time has published bulletins outlining recommended standards of purity. These have usually been adopted by the various state health departments, the American Water Works Association, and other organizations interested in public health and safe water supplies. The current standards can be found in reference (1). The American Public Health Association has also been very helpful in this program and, from time to time, has published *Standard Methods for the Examination of Water and Sewage.* Several of the latest editions have been published jointly by the American Public Health Association (1). In these bulletins are to be found the recommended methods of analysis to be used for the examination of water. Also helpful in this program have been the contributions of many engineers, public health officials, and others concerned with the development of methods of purification. These have now been perfected to the point where moderately polluted supplies can be rendered safe and relatively free from undesirable tastes and odors.

Testing

Before discussing the standards and methods that should be used for testing of water, it is desirable to review the background information concerned with the philosophy behind these tests. Originally, a serious problem presented itself to the analyst. What kind of test can he perform on a sample of water to determine whether or not it is safe to drink? The danger stems from the pathogenic bacteria that may be in the water. Detecting the presence of such bacteria is much more difficult than assaying for undesirable chemicals, since one individual disease-producing organism can multiply rapidly. When a few of these pathogens are mixed with many other bacteria it is difficult, if not impossible, to find them. Toxic chemicals, on the other hand, must be present in concentrations high enough to exert their effect and, therefore, high enough to detect. In the case of the pathogenic bacteria the test is so difficult and uncertain that negative results mean very little. The uncertainties involved in detecting pathogens even when they are present preclude direct tests because negative results would be meaningless. Instead, indirect evidence that may have a high degree of correlation with the presence of disease-producing organisms must be depended upon.

The first such test to suggest itself was a determination of the nitrogen content, on the assumption that if water contained disease-producing organisms it would be because of sewage contamination, and this would bring with it a fair amount of nitrogenous matter. Consequently, a test for nitrogen could indicate the possible presence of sewage. It was soon found, however, that there was very little correlation between the nitrogen content of the water supply and its known sanitary qualities. Numerous water supplies were found to contain relatively small amounts of nitrogen and yet did contain pathogenic organisms. On the other hand, many supplies were also found that contained a good deal of organic nitrogen and yet showed no evidence of sewage pollution or of organisms that could cause disease. Obviously, this lack of correlation would be the result if water could pick up nitrogenous matter from sources other than sewage. This is reasonable.

Other chemical tests undoubtedly suggested themselves to those who were concerned with this problem, but all such tests failed for the same reason. More reliable methods were developed when bacteriological analysis was resorted to. Here again, for the reasons cited above, indirect evidence must be relied upon. This means that certain index organisms that would come from sewage must be depended upon. The presence of the index organism would then indicate that the water was contaminated with sewage and, therefore, might contain pathogenic microorganisms. Three different groups of bacteria have been suggested as possible suitable index organisms. One is the coliform group (also called colen group, or coli group), which comprises a group of lactose-fermenting Gram-negative rods that are commonly found as intestinal parasites. The second is a group of anaerobic spore-forming bacteria, belonging to the species *Closteridium welchii*, or organisms closely related to this group. These also are believed to be common intestinal inhabitants. The third is a group of streptococci that are commonly found as intestinal parasites and are very often referred to as the sewage streptococci. To be an ideal index organism, certain criteria must be satisfied. The group must be present in any water supply that contains pathogenic organisms, it must be easy to test for, and it should not be commonly encountered in nature outside of the intestinal tract or sewage. While there may be some difference of opinion among bacteriologists as to which of the three groups mentioned above would be best, American bacteriologists appear to agree that the coli group is the one of choice. There are certain disadvantages associated with any one of these three groups, but since an ideal index organism may not be available, it is necessary to choose the one with the fewest disadvantages. The sewage streptococci are rather difficult to detect and the anaerobic organisms are hard to isolate, as well as being found rather widespread in nature outside of the intestinal tract. Even the coli group has its disadvantages in that there are some organisms growing in soil that are very similar to those found in the intestinal tract and, therefore, if this is to be used as the index group, it may be necessary to differentiate between soil forms and intestinal forms.

In reference (1), the coli group is defined as follows: "The coliform group should be considered to include all aerobic and facultative anaerobic Gram-negative nonspore-forming bacteria which ferment lactose with gas formation." This definition will include not only what most bacteriologists consider to be the coli group but also the aerogenous group (the soil forms) which have many characteristics in common with the former. With the above information, we are now in a better position to appreciate the significance of the standards that have been suggested by the Public Health Service, and which have been adopted by the American Water Works Association. These read in part as follows (1):

"2.1 The water supply shall be: (*a*) Obtained from a source free from pollution; or (*b*) Obtained from a source adequately purified by natural agencies; or (*c*) Adequately protected by artificial treatment.

"2.2 The water supply system in all its parts should be free from sanitary defects and health hazards, and all known sanitary defects and health hazards shall be systematically removed at a rate satisfactory to the reporting agency and to the certifying authority. Approval of public water supplies by the reporting agency and the certifying authority will be conditioned by the existence of: (*a*) Rules and regulations prohibiting connections or arrangements by which liquids or chemicals of unsafe, unknown, or questionable quality may be discharged or drawn into the public water supply; (*b*) Provisions to enforce such rules and regulations effectively on all new installations; and (*c*) A continuing program to detect health hazards and sanitary defects within the water distribution system.

"3. As to Bacteriological Quality:

"3.1 Sampling. The bacteriological examination of water considered under this section shall be of samples collected at representative points throughout the distribution system."

Population served	Minimum number of samples per month
2,500 and under	1
10,000	7
25,000	25
100,000	100
1,000,000	300
2,000,000	390
5,000,000	500

The minimum number of samples to be collected from the distribution system and examined by the reporting agency or its designated representatives each month should be in accordance with the number as indicated in the table.

"3.25. The procedure given using a standard sample composed of five standard portions, provides for an estimation of the most probable number of coliform bacteria present in the sample as set forth in the following tabulation:

Number of portions		Most probable number of coliform bacteria per 100 ml.	
Negative	Positive	When 5–10-ml. portions are examined	When 5–100-ml. portions are examined
5	0	Less than 2.2	Less than 0.22
4	1	2.2	0.22
3	2	5.1	0.51
2	3	9.2	0.92
1	4	16.0	1.60
0	5	*More than 16.0*	*More than 1.60*

"4. As to the Physical and Chemical Characteristics:

"4.1. Physical characteristics. (The requirements in section 4.1 relating to turbidity and color shall be met by all filtered water supplies. Turbidity and color limits for unfiltered waters and the requirements of freedom from taste or odor for either filtered or unfiltered waters should be based on reasonable judgment and discretion, giving due consideration to all the local factors involved.) The turbidity of the water shall not exceed 10 ppm (silica scale) nor shall the color exceed 20 (platinum-cobalt scale). The water shall have no objectionable taste or odor.

"4.2. Chemical characteristics. The water shall not contain an excessive amount of soluble mineral substance, nor excessive amounts of any chemicals employed in treatment. Under ordinary circumstances, the analytical evidence that the water satisfies the physical and chemical standards given in sections 4.1 and 4.21 and simple evidence that it is acceptable for taste and odor will be sufficient for certification with respect to physical and chemical characteristics.

"4.21. The presence of lead (Pb) in excess of 0.1 ppm, or of fluoride in excess of 1.5 ppm, shall constitute grounds for rejection of the supply.

"4.22. The following chemical substances which may be present in natural or treated waters should preferably not occur in excess of the following concentrations where other more suitable supplies are available in the judgment of the certifying authority.

"Copper (Cu) should not exceed 3.0 ppm.

"Iron (Fe) and manganese (Mn) together should not exceed 0.3 ppm.

"Magnesium (Mg) should not exceed 125 ppm.

"Zinc (Zn) should not exceed 15 ppm.

"Chloride (Cl) should not exceed 250 ppm.

"Sulfate (SO_4) should not exceed 250 ppm.

"Phenolic compounds should not exceed 0.001 ppm in terms of phenol.

"Total solids should not exceed 500 ppm for a water of good chemical quality. However, if such water is not available, a total solids content of 1,000 ppm may be permitted.

"For chemically treated waters, i.e., lime softened, zeolite or other ion exchange treated waters, or any other chemical treatments, the following three requirements should be met:

"(1) The phenolphthalein alkalinity (calculated as $CaCO_3$) should not be greater than 15 ppm plus 0.4 times the total alkalinity. This requirement limits the permissible pH to about 10.6 at 25° C.

"(2) The normal carbonate alkalinity should not exceed 120 ppm. Since the normal alkalinity is a function of the hydrogen ion concentration and the total alkalinity, this requirement may be met by keeping the total alkalinity within the limits suggested below when the pH of the water is within the range given. These values apply to water at 25°C.

"(3) If excess alkalinity is produced by chemical treatment, the total alkalinity should not exceed the hardness by more than 35 ppm (calculated as $CaCO_3$)."

Presumptive evidence of the presence of the coli group of organisms is obtained by inoculating graduated amounts of the water to be tested into tubes or bottles of lactose broth which contain inverted gas traps. The concentration and volume of the medium in these tubes or flasks must be

pH range	Limit for total alkalinity (ppm as $CaCO_3$)
8.0 to 9.6	400
9.7	340
9.8	300
9.9	260
10.0	230
10.1	210
10.2	190
10.3	180
10.4	170
10.5 to 10.6	160

adjusted to the size of the sample of water to be used as an inoculant. If a large volume of water, such as 10 or 100 ml., is to be used, then the volume in the tube or flask must be 10 or 50 ml., respectively, and the strength of the broth should be double or triple strength. If gas is produced in the tubes within 24 or 48 hours, one must presume the presence of the coli group. The evidence, however, is not conclusive since there are a few other organisms such as some of the spore-forming anaerobes that can also produce gas from lactose.

To obtain more conclusive evidence it is, therefore, necessary to perform further tests on each of the tubes or bottles in which gas is found. This is generally spoken of as the confirmed test and is usually performed by streaking one or more plates of eosine methylene blue lactose agar from each of the tubes or flasks that show gas formation. The plates must be streaked in such a fashion as to produce distinct colonies that are separated at least 0.5 cm. from each other. These plates are then incubated at 35–37°C. for 24 hours after which they are examined. If typical *Escherichia coli* colonies are found on these plates, the confirmed test may be considered positive. Typical coli colonies are small, from a quarter to a half a centimeter in diameter, have smooth edges, a deep blue-black color, and show a characteristic metallic sheen. Before declaring the test positive, if typical colonies do appear, it is advisable to make Gram stains of some of these colonies to ascertain that the organism is Gram-negative. Some strains of *E. coli* may produce colonies that are not typical and, therefore, if such are found, it may be necessary to carry out further tests to ascertain whether or not the organisms are members of the genus *Escherichia*.

In place of using the agar plates, the confirmed test may be performed by inoculating samples that show gas from the tubes of lactose broth into tubes of brilliant green lactose bile broth. The brilliant green and the bile in this medium are designed to prevent the growth of lactose-fermenting organisms which do not belong to the coli group. If gas in any amount is found in the inverted gas traps of the tubes of this medium after 48 hours of incubation, the confirmed test may be considered positive. The indicator in the brilliant green lactose bile broth may be decolorized before the end of the 48-hour incubation. In this case, a further test should be made to ascertain the nature of the organism that was responsible for the formation of the gas.

If the evidence obtained from the confirmed test is not conclusive, the completed test should be carried out. If the confirmed test consisted in streaking the plates of eosine methylene blue agar, and atypical colonies are found, then one should get samples from some of the most typical colonies and inoculate these on ordinary agar slants and also into fresh tubes of lactose broth. If the confirmed test was made on a liquid medium, that is the brilliant green lactose broth, then the completed test will consist in streaking eosine methylene blue plates, and, after 48 hours of incubation at 37°C., selecting typical coli colonies, or colonies that are the most similar to the coli colonies, and again inoculating these onto agar slants and into fresh tubes of lactose broth. After these have been incubated for 48 hours at 37°C., a Gram stain should be made from the agar slant growth and if this proves to be a Gram-negative organism with gas forming in the lactose broth, the completed test is considered positive. One can then conclude that the gas was produced from a member of the coli group. If, from the stain preparation, the organism does not prove to be a Gram-negative nonspore-forming rod, and if no gas is produced in the lactose broth, the test should be considered negative.

At times it may be desirable to determine not only whether or not the coli group is present but also the relative number of these organisms present. This can be done by running a quantitative presumptive test, in which case a series of graduated amounts of water are inoculated into several tubes of lactose broth and a record kept of the number of tubes that produce gas. In each case, it will

be necessary to confirm all tubes where gas is produced and, by referring to suitable probability tables, one can calculate from the number of tubes that show gas, the most probable number of lactose-fermenting organisms present in the sampled water.

In addition to the above bacteriological analysis, it is also useful to determine total number of bacteria that are present in the water by making ordinary plate counts on nutrient agar which is incubated at 37 °C. For this purpose, 1-ml. amounts of suitable dilutions are placed in each of several Petri plates. On this is poured melted nutrient agar cooled to 45 °C.; before the agar is allowed to harden, the plates are rotated in a figure eight so as to mix the nutrient agar with the sample. After the agar has hardened, the plates are incubated in an inverted position at 37 °C. for 48 hours, after which the number of colonies are counted. While the total count in itself may not have any sanitary significance, a high count indicates the presence of nutrient in the water upon which organisms can grow and this is an undesirable condition. The plate count may also be useful in testing treated water supplies where a high count would indicate faulty treatment.

In addition to the bacteriological analysis, additional useful and necessary information regarding the suitability of the water is obtained from physical and chemical analysis. These will be discussed briefly but for precise details on methods and procedures, see reference (1).

Turbidity. Turbidity is due to finely divided inorganic or organic matter such as microorganisms, other insoluble organic material, silt, and similar substances. Suspended matter and turbidity are not synonymous. Suspended matter represents a residue on evaporation that is not in solution, while turbidity is an approximation of suspended matter obtained by optical measurement. This is determined by observing the interference to the passage of light through a sample of the water as compared to a standard. The turbidity is recorded in units obtained by comparison with standards made by suspending finely divided fuller's earth in distilled water. To comply with the standards set up by the U.S. Public Health Service mentioned earlier, this turbidity should not exceed 10 p.p.m.

Odor. Odor in water is usually associated with objectionable substances that result from pollution, decomposing organic matter, microorganisms, or industrial waste. The substances responsible for these are volatile and are present in amounts too small to permit detection by ordinary chemical means. The amount and character must therefore be detected by the sense of smell, which is very sensitive but lacks precision and does not permit the establishment of absolute odor standards.

The amount is determined by observing the maximum dilution that can be made into odor-free water to permit detection. A series of dilutions on a geometric scale are prepared with an odor-free dilution water so as to give samples for testing of 200 ml. Each of these is tested for odor; at 24–25 °C. for "cold odor" or at 50–60 °C. for "hot odor." A record is kept of the maximum dilution at which an odor is perceptible and the ratio of total volume to the volume of sample is called the odor number.

Color. The color of water should be determined only after the suspended matter has been removed; in other words, the true color is due to substances in solution. If the water contains suspended matter, it should first be removed by centrifuging. Removal of suspended matter by filtration is not permissible because the filters may adsorb some of the color. Sometimes it may be desirable to determine the color before suspended matter has been removed. This is generally referred to as the apparent color. The color is determined by a comparison with standards made up with salts of platinum and cobalt, a unit being considered that amount of color produced by one milligram of platinum per liter. The standard is made by dissolving 1.245 g. of potassium chloroplatinate, K_2PtCl_6, containing 0.5 g. of platinum, and 1 g. of crystallized cobaltous chloride, $CoCl_2.6H_2O$, containing about 0.248 g. of cobalt, in water with 100 ml. of concentrated hydrochloric acid, and diluting to 1 liter with distilled water. This solution has a color of 500. The ratio of cobalt to platinum may be varied to match the hues found in water in certain special cases. To be satisfactory the color should not exceed 20.

Residue. The residue represents the material remaining after the water has been evaporated. If the suspended matter is removed first, a determination gives the dissolved residue, while if determinations are made on the original water with suspended matter left in, it is called the total residue. In either case the water is evaporated and the solids are dried to a constant weight at 103 °C., preferably in a platinum crucible. If the solids are ignited, the weight of the remaining materials is called the fixed solids, these being the total fixed solids or the dissolved fixed solids, as the case may be. To determine the suspended residue separately, a measured quantity is filtered through a previously prepared Gooch crucible that has a 2-mm. mat of asbestos fiber which has been heated to a constant weight at 103 °C. A sufficiently large sample of water should be filtered through this crucible to produce from 50 to 100 mg. of residue. This is then dried at 103 °C. to constant weight.

Hardness. When calcium and magnesium and, to some extent, iron and aluminum are present in water it is difficult to obtain a lather with the use of ordinary soap. Enough must first be added to precipitate the ions which produce insoluble soaps. Water that requires an excessive amount to form a lather is referred to as "hard water," usually expressed in terms of calcium carbonate, or the calcium carbonate equivalent of the calcium and magnesium. In many waters such hardness is due to salts of calcium and magnesium carbonates or the corresponding bicarbonates, while in other cases the sulfates and chlorides of these metals may be the principal contributors. When the total hardness is greater than the carbonate and bicarbonate alkalinity the amount equivalent to the alkalinity is called the carbonate hardness. The amount in excess of this is referred to as the noncarbonate hardness. When the total hardness is equal to or less than the sum of the carbonate and bicarbonate alkalinity, there is no noncarbonate hardness. *Standard Methods for the Examination of Water and Sewage* lists four general methods of determination:

1. *Total hardness by calculation.* Hardness is calculated from an independent determination of the calcium, magnesium, iron, and other metals that produce insoluble soaps.

2. *The palmitate method.* A standard solution of potassium palmitate is added to the water to precipitate the calcium and magnesium from solution as the insoluble soaps. The addition of an excess of potassium palmitate over that required for the complete precipitation of the calcium and magnesium will produce by hydrolysis a solution which reacts alkaline to phenolphthalein. From the amount of potassium palmitate solution which has been added when the solution becomes alkaline one can calculate the total hardness. In this way, the magnesium hardness can be determined separately by first precipitating the calcium with a solution of sodium oxalate. Magnesium is left in the solution and this can then be titrated with palmitate. The calcium hardness may then be calculated from the difference between the total hardness as obtained above and the magnesium hardness.

3. *The soap method.* This actually measures the soap-consuming power of the water and is made by adding to the water a standard soap solution until just enough has been added to give a permanent lather. By noting the total amount of soap that must be added to reach this point, one can calculate the total hardness. By using this method, one can also determine the calcium and magnesium hardness, because if the solution is adjusted to a pH of 11.7–12.0 with ammonium chloride the soap will react only with the calcium. In such a solution, one can determine the calcium hardness and, hence, by the difference between this and the total hardness, estimate the magnesium hardness.

4. *Schwarzenbach titration method.* This method, also known as the complexiметric or EDTA titration method and the Versenate method, is a rapid and precise method that has been widely used and is now a standard method. It utilizes the color change of an indicator during the reaction of ethylenediaminetetraacetic acid with calcium and magnesium ions. See p. 931; Vol. 12, p. 177.

Acidity. Some waters may present an acid reaction, usually due to the presence of uncombined carbon dioxide, mineral acids, or salts of strong acids and weak bases. It is determined by titration with a 0.02 *N* carbonate-free sodium hydroxide solution using either methyl orange or phenolphthalein as the indicator. With phenolphthalein, the result is recorded as the total acidity, with methyl orange as mineral acid acidity.

Alkalinity. Many waters are alkaline. Alkalinity is determined volumetrically by titration with a 0.02 *N* sulfuric acid solution to a phenolphthalein or methyl orange end point. Such alkalinity is usually caused by the presence of carbonates, bicarbonates, hydroxides and, less frequently, by other alkalies such as borates, silicates, or phosphates.

pH Values. In addition to the titrable acidity or alkalinity, it is also useful to know the pH of the water. This can be determined with any one of the standard pH meters, using glass electrodes. It may also be determined by suitable indicators. See *Indicators*; *Hydrogen-ion concentration.*

Chloride. There are cases where a determination of chloride may be very important in municipal water, because a sudden increase in chloride will generally indicate pollution from industrial or domestic wastes. This will be particularly true if the water direct from the supply is low or free from chlorides. Furthermore, since chlorides are not affected by microbial activities, a change in the chloride content from the raw water to samples collected in the treatment works or distribution system will indicate the admixture of other waters. Chloride may be determined (Volhard method) by adding an excess of a standard silver nitrate solution (0.01711 *N*) to precipitate the chlorides and then titrating the excess nitrate present with thiocyanate using a nitrobenzene and ferric alum indicator. As an alternative the Mohr method may be used in which potassium chromate is added as an indicator. When the chlorides have been precipitated, the silver will combine with the chromate to produce a red precipitate.

Chlorine. Chlorine is commonly used as a disinfectant in the treatment of water supplies; it is

therefore important to determine residual chlorine, because this indicates how well the public is protected against possible contaminants. At present, there is no completely satisfactory direct method for this, but reasonably good results are obtained with a colorimetric method using *o*-toluidine, or with the iodometric method. In the presence of residual chlorine *o*-toluidine develops a characteristic color, the intensity of which is a function of the concentration of the halogen. This can be established by comparing the color in the unknown with previously calibrated standards. The iodometric method depends upon the liberation of iodine from potassium iodide by chlorine and the subsequent titration of the free iodine with standard thiosulfate, using the starch indicator for the end point. The iodometric method is more precise than the *o*-toluidine test, when the amount of residual chlorine is in excess of 1 p.p.m. With either test there are a number of substances that can interfere and, for this reason, it is important that the method as described in reference (1) be followed precisely.

There may be a number of substances in water that react with chlorine, hence, the residual will generally be considerably less than the amount added. That portion that disappears immediately does so because it serves as an oxidizing agent against reducing substances in the water. In general, this is referred to as the "immediate chlorine demand," and must be known before one can judge the amount of chlorine that should be added to obtain the desired disinfection. This immediate demand varies with the kind of water, the amount of chlorine applied, the time of contact, and the temperature. A consideration of the chlorine demand becomes particularly important in the "break point" method of chlorination (see p. 960).

Numerous substances affect the odor and taste of water, following chlorination. These may represent phenols that are introduced from wastes or phenol-like substances produced by various microorganisms, such as algae and protozoa. There is no suitable method for the determination of such substances other than the development of undesirable flavors. If they are present, it may be necessary to inaugurate special methods of treatment to counteract them.

Fluoride. It is now generally accepted that a small amount of fluoride in drinking water will increase the resistance of the tooth enamel to decay or acid corrosion. Thus in areas where there is a high fluoride content in the drinking water there is a decreased incidence of dental caries. Many communities that have a low fluoride content in their raw water have now adapted fluoridation (the adding of fluoride to the water supply to reduce the incidence of dental caries). Excessive amounts of fluoride (above 1.5 p.p.m.) are undesirable because they may cause mottled teeth, a condition in which the tooth enamel will be marred by brown specks or spots that cannot be removed. In view of the importance of fluoride, it is desirable and often necessary to test for it. This can be done by a colorimetric method in which the fluoride in the water reacts with the zirconium in an acid zirconium alizarin reagent to form a nonionized zirconium fluoride salt. This decreases the color of the reagent. The quantity of fluoride is determined by comparing the amount of color remaining in a measured amount of reagent added to the sample of water with that remaining in a like amount of reagent in standards made by adding known quantities of fluoride to distilled water.

Miscellaneous Substances. In addition to the analyses mentioned above, it is well to determine the concentrations of a number of species of ions that are usually present in water, for example, carbonate, bicarbonate, iodide, sulfate, and the various types of phosphate ions, as well as the silica, arsenic, copper, iron, aluminum, lead, manganese, zinc, potassium, sodium, and nitrogen as ammonia, organic, and nitrate and nitrite. Information on methods for the determination of these various substances may be found in reference (1).

Treatment of Water

Most municipalities must use a source of water in which the probability of pollution is rather high. Certainly, all our natural rivers and lakes and even the water stored in most reservoirs may be subjected to pollution, and generally cannot be considered safe for drinking purposes without some form of treatment. Water treatment, therefore, is a practical necessity in all municipalities. The type and extent of treatment will vary from city to city, depending upon the conditions of the raw water. Treatment may comprise various processes used separately or in combinations, such as storage, aeration, sedimentation, coagulation, rapid or slow sand filtration, and chlorination, or other accepted forms of disinfection.

Sedimentation. When surface waters serve as a municipal water supply, it is

generally necessary to remove suspended solids, which can be accomplished either by plain sedimentation (*q.v.*) or sedimentation following the addition of coagulating chemicals. In the water from most streams that are suitable as a source of supply, the sediment is principally inorganic, consisting of particles of sand and clay and small amounts of organic matter. In this water there will also be varying numbers of bacteria, depending upon the amount of bacterial nutrients present, coming from sewage or other sources of organic matter, and upon the prevailing temperature. Many of the bacteria may have come from the soil and, as a result, during a season of high turbidity when there is a large amount of eroded soil in the water, the bacterial count from this source may be relatively high. If the organisms are derived from sewage pollution, the number will be highest during periods of low flow when there is less dilution, and at this time the turbidity will, in general, be low. The amount of sediment may vary a great deal from one river to another, depending upon the geological character of the various parts of the drainage system. Thus, the Missouri River carries much more suspended matter than does the water in the upper portions of the Mississippi River. The size of the suspended particles can also vary greatly. In some waters the clay particles may be extremely fine, in fact, they may be smaller than bacteria.

Where plain sedimentation is to be resorted to, the longer the period of quiescence, the better will be the results. The ideal situation would be where a municipality can make use of either artificial or natural lakes into which the water can be pumped and where it can remain for several days or weeks before it is taken into the plant for treatment. During this time most of the settable matter will be removed and, in addition, owing to the growth of various kinds of microorganisms, the character of the water can be changed profoundly. In most cases these changes will ease the treatment problem and, furthermore, large reservoirs will permit the shutting down of the pumps in periods of very high flow when the raw river water would be very turbid and high in suspended matter. Long storage periods, however, may have some accompanying disadvantages. During the storage of the water in large reservoirs, through the influence of higher temperatures and light, many types of microorganisms may develop, in fact, in some cases the growth can be quite abundant. Accompanying the growth, particularly of the algae, some protozoa, bacteria, and species of streptomyces compounds may be liberated that are difficult to remove and that can react with chlorine to impart bad taste or odor. Excessive growth of such organisms usually can be prevented by treating the water with suitable amounts of copper sulfate.

The time required for satisfactory sedimentation differs for different waters, and generally must be established by actual experiments. Some waters can be clarified satisfactorily in a few days, while others may require weeks and months. As far as total weight of sediment is concerned, the bulk of it is probably removed in a few days, but this may not bring about a corresponding change in the appearance of the water, since the smaller particles may have greater influence than the large ones upon the apparent color and turbidity. When plain sedimentation is used primarily as a preliminary treatment, a high degree of clarification is not needed and, as a result, shorter periods of settling are adequate. For sewage-polluted water, sedimentation alone is inadequate treatment, as the pathogenic organisms would not be eliminated by reasonable periods of settling. Under such conditions, when further treatment is necessary, a short period of 24 hours of sedimentation may be sufficient. Changes other than those brought about by the sedimentation alone generally go on within these reservoirs, particularly if stored for an extended period. Organisms that are present can con-

sume a great deal of the organic matter; the exhaustion of the food supply can result in a decrease in the number of organisms present; in open reservoirs the light may exert a disinfecting action; and the competition between various forms of microorganisms may eliminate some of the undesirable ones. These beneficial changes may be counteracted to some extent by the growth of algae and some other organisms mentioned earlier.

The sediment that forms at the bottom of the reservoirs or lakes will contain a fair amount of organic matter as well as the inorganic silt that settles to the bottom. In this sediment there will usually develop a characteristic flora, largely anaerobic, that can digest the settled organic matter and bring some of it back into solution. While this may not be noticeable under ordinary circumstances, it can become an important consideration during certain seasons of the year when temperature changes in the water can cause an overturning with a corresponding resuspension of much of the material that had settled out.

Treatment with Coagulants. A number of chemicals will combine with water or the constituents present therein to produce a flocculent or gelatinous precipitate which aids considerably in the clarification during sedimentation. During the formation and settling of the flock, many of the finely divided suspended particles, including microorganisms, are collected and some of the dissolved substances, particularly those that impart color, are absorbed. The use of coagulants was originally intended as pretreatment before rapid sand filters, but the good results obtained have resulted in their use prior to sedimentations that are not connected with such filters. Of the various chemicals that can be used for this purpose, aluminum sulfate, commonly called "alum," is employed most extensively. Ferric salts are acceptable substitutes, especially if the pH of the water is not suitable for alum coagulation. These trivalent cations are very effective in precipitating negative colloids. Both aluminum and iron form gelatinous precipitates in slightly alkaline solutions, and the extent to which these added salts participate in the precipitation will depend to a large extent upon the pH of the water. Since the amount of precipitate and the efficiency of removal of suspended matter are dependent upon a favorable pH, it is often possible to improve the effectiveness of the alum treatment by a prior adjustment of pH. In most cases, such adjustments are necessary when there is insufficient alkalinity.

The amount of alum required for proper clarification and color removal is dependent upon the character of the water, the methods of handling, and length of sedimentation to be used. The amounts used in practice vary from less than one grain to approximately five grains per gallon. (One grain = $\frac{1}{7000}$ lb., one grain per gallon = 17.2 mg./l.) The amount needed in any one case has to be determined by experiment.

The coagulating chemicals must be added to the water as it flows into the treatment plant, necessitating a continuous feed, proportioned to the flow of the water. In some cases, the coagulant is dissolved in a small amount of water to give a strong solution and then fed into the raw water. In other cases, the dry powders are mixed with the incoming waters by proportioning machines. Immediately after the coagulant has been added, the mixture enters a chamber where there is a rapid or violent stirring, so as to mix the chemicals uniformly with the water. After this, the water enters another chamber, where it remains for a period of from 15 to 20 minutes and where it is stirred slowly. During this slow agitation the precipitate forms and increases in size. The slow mixing also permits the precipitate to sweep through the water and thus enables it to occlude more of the suspended matter and also adsorb

more of the dissolved substances. This agitation can be accomplished either by having the liquid flow through a narrow channel, over and under a series of baffles, or having it mixed in a rectangular tank by mechanical devices. If this period of mixing is not employed, a larger quantity of chemical has to be added to accomplish the desired results. In some localities it has been found desirable to chlorinate the water before it is treated with the coagulating chemicals (see p. 958).

After the floc has formed and after the period of slow mixing, the water is run into settling basins where the precipitate can be allowed to settle. One of several types may be employed. One is an intermittent type which operates on a fill-and-draw basis, and the other is a continuous type in which the water flows through at a slow rate. In the former, the water after filling remains quiescent for a period of from 4 to 6 hours. During this time another basin is being filled, so where the fill-and-draw method is used several basins are needed. When the floc has settled, the clear water is drained from the surface until the level of the floc is reached. The basin is then either emptied into the waste line or it is immediately refilled for another cycle. This method gives somewhat better results in the removal of precipitate but suffers from the disadvantage of requiring more settling basins and more loss of head, because if the water is delivered to filters from the settling basins, the level in the filters must be below the lowest point from which it is drained from the settling basin.

In the continuously operating basins, the water is run in at one end and allowed to pass slowly through the chamber and emerge from the other end as clarified water. These basins are large enough so that the theoretical detention period is from 2 to 8 hours, that is, large enough so that it would take from 2 to 8 hours to fill the empty tank at the normal rate of flow. The actual detention is usually less than the theoretical figure because the water does not generally pass uniformly through all cross sections of the tank. In many installations these tanks are constructed so as to depend upon manual operation for the removal of the solids, which is done from time to time by taking the unit out of service, draining the water, draining and hosing the bottom, and cleaning the tank before putting it back into service. To facilitate such cleaning, the bottoms of the tanks are generally constructed so that they slope toward the point where there are openings into the waste line. In modern practice settling basins are provided with mechanical scrapers that continually push the solids into sludge pits where they can be removed with pumps. Many of these are built circular rather than rectangular, with provisions for the water to enter through a center well and the removal of the effluent over a circular weir which is extended around the outer circumference. The mechanized tanks have the advantage that they can be kept in continuous service, and are particularly desirable in installations where a large amount of sediment must be removed. They are less efficient than the fill-and-draw type in the removal of the floc, but this may be an advantage in that the floc that remains may aid in the clarification of the water on the rapid sand filter. If slow sand filters are used, the fill-and-draw types are more preferable. See also Vol. **12,** p. 129.

Sand Filters. From the settling basins, the water is delivered to the sand filters by gravity or by pumps. One of two types are commonly in use—the slow sand filter or European type, and the rapid sand filter or the American type. The *slow sand filter* is made in a watertight reservoir usually covering an area of ½ to 1½ acres; in the bottom of this is provided a system of drains which are covered first with broken stone and then with a series of layers of gravel of decreasing size, each layer from 2 to 3 in. thick, with a final size small enough to be able to retain sand. On top of this gravel

is then placed from 4 to 5 ft. of relatively fine sand. See Vol. **6**, p. 517. When the filter is first put into operation the water is generally sent in through the underdrains until the bed fills and there is from 3 to 4 in. of water on top of the sand. The balance of the water can then be delivered from the top, until there is a depth of 4–5 ft. of water, giving sufficient pressure to allow the proper rate of flow through the sand. This should be from 2 to 6 million gallons per acre of surface per day. As the filter continues in operation, a fine sediment accumulates at the surface and this increases the resistance to the flow of water that must be compensated for by a greater depth of water above the sand. After some weeks or months of operation, the accumulation of this deposit may become so great that an excessive head is required. At this time the bed has to be taken out of operation. The water must be permitted to drain away and from 2 to 3 in. of the sand is removed from the surface. This sand is generally taken to the scrubbers where it is cleaned and either placed into another bed or is stored for future use. After this cleaning, the bed is put back into operation again by first feeding filtered water through the underdrain until 2–3 in. of water stands above the sand, and then other water to be filtered is run in from the top, and thus the cycle is repeated.

As the sand filters continue to operate, their efficiency in general increases, and it has been shown that the removal of suspended matter and bacteria is brought about not by a mechanical removal but rather by a process of adsorption; this is facilitated by a growth of microorganisms on the surface of the sand particles. This growth consists largely of bacteria belonging to the group *Caulobacteriales*. These organisms attach themselves to solid surfaces by means of short stocks, at the end of which the organisms grow. These stock bacteria form virtually a microscopic forest on the surface of the sand particles, and as the water percolates through this microscopic forest, many of the bacteria and other suspended materials are removed. It is because of development of this flora on the sand particles that the filters improve with age. After one of these slow sand filters has been in use for some time, it becomes very efficient in the removal of microorganisms, finely divided suspended matter, and dissolved compounds that impart color to the water. The number of microorganisms found in the effluent will generally be less than 2% of the number in the influent. From 10 to 20% of the color may be removed and organic matter to the extent of about 50%. In all probability, most of the organisms that are found in the effluent of the slow sand filters come from the growing flora rather than from those brought in with the raw water, the actual removal of entering organisms is, therefore, close to 100%. However, one cannot depend upon the units for complete removal of undesirable bacteria because it has been shown that epidemics of typhoid fever have occurred in communities where the water is so filtered.

After the filters have been cleaned a number of times, the thickness of the sand is cut down so much that new or clean sand needs to be put back. At the last cleaning before this is done, it is best to remove more than 2 in. of the old sand. It is also good practice to rake the remaining sand so as to break up any irregularities that might permit channeling of water. Also, this raking will provide aeration and aid in the removal of organic matter that has accumulated.

In some places the slow sand filters have been constructed without covers, but where this is done in areas having severe winters, the formation of ice interferes considerably with the cleaning of the beds. It has, therefore, been found desirable, in spite of higher costs of construction, to provide covers for these beds.

The construction of the *rapid sand filter* is about the same as the slow. However, the method of operation is quite different. They are constructed in small sections because of the need for backwashing, thus reducing the size of the pumps needed for this cleaning operation. The depth of sand in these filters is somewhat less than in the slow filters and the operating head is much higher, the water depth being from 10 to 12 ft. The rate of filtration is from 100 to 125 million gallons of water per acre per day, and because of this high rate the area required is relatively small. With slow sand filters it is sometimes possible to obtain adequate clarification by filtration alone. This is not possible with rapid sand filters, treatment with coagulants being an absolute necessity. Here, also, it is desirable to leave some of the precipitate in the water as it enters the sand filters in order to build up a film on the surface of the sand to aid in the removal of suspended matter and bacteria. This means that the sludge accumulates rather rapidly and that the sand has to be cleaned often, in fact backwashing may be necessary every 10–24 hours. During backwashing filtered water is pumped back through the sand from the underdrains under sufficient pressure to bring about a slight separation of the sand grains, causing the sand to rise in the bed, become agitated, and to separate the entrapped turbidity from the sand. The cleaning is sometimes facilitated by a mechanical mixing of the sand while it is being backwashed or by blowing air into the sand bed at this time. The backwash water with the sludge it removes is run into gutters placed at a proper level above the sand and from there is drained into the waste line. After a few minutes of backwash the water will come through clean and the bed is then put back into service. See Vol. **12,** p. 140.

In a single plant there will be many of these individual units so constructed and arranged that any one unit can be taken out of service without interfering with the operation of the others. In such plants, it is necessary to have continuous expert supervision so the sand beds can be kept in good operating condition at all times. The removal of bacteria by the rapid sand filter may not be quite as high as that of the slow filter but with proper coagulation preceding the filtration, an adequate overall efficiency can be maintained.

Disinfection. Since sand filters cannot be depended upon to remove all the pathogenic organisms that might be present, it is necessary as an extra safeguard to introduce some disinfectant into the water after it emerges from the sand bed and before it is put into the distribution system. The available and permissible disinfectants are chlorine, hypochlorite, ozone, and ultraviolet light. Chlorine is the agent used, in most plants in the form of a strong solution of chlorine in water, which has been produced in chlorinators that dissolve gaseous chlorine in the proper proportions. This solution is added as the water emerges from the sand filter. The gaseous chlorine in turn is obtained from liquid chlorine in cylinders or tank cars. Time is required for the chlorine to kill the pathogenic bacteria, and, therefore, it is desirable to retain the water in reservoirs for a period of time before it is pumped into the distribution system. The quantity of chlorine required will vary from time to time, depending upon the nature of the water, the amount of organic matter present, and the residual that needs to be maintained. Most of the pathogenic microorganisms will be killed with a content of chlorine varying from 0.3 to 0.4 p.p.m., but in order to have this amount of chlorine available, it is necessary to add more because some of it will be used for the oxidation of organic matter. The amount that needs to be added, therefore, will vary from 0.7 to 1.5 p.p.m. Further, it is also desirable to maintain a residual of chlorine in the water throughout the distribution system to take care of pathogenic

organisms that might get into the water by accident after it leaves the treatment plant. When chlorine is used alone as a disinfectant, it is sometimes difficult to maintain the desired residual because it reacts so readily with organic matter, particularly growths that can occur in pipelines, and thus, in order to have a residual in the most distant parts of the distribution system, excessive quantities of chlorine will have to be added from the beginning. It has been found that by using a mixture of chlorine and ammonia this objection can be overcome to some extent, since with this mixture chloramines (*q.v.*) are produced which are more stable than free chlorine.

In most waters a relatively high concentration of chlorine will impart an undesirable taste and odor. In pure distilled water this will not happen until a level of about 3 p.p.m. is reached, which is considerably more than is needed for proper disinfection. However, in many surface water supplies these tastes and odors can develop at much lower concentrations, so that consumers may object to the "chlorine taste" even when inadequate amounts for proper disinfection have been added. It is known that some organic compounds can react with chlorine at rather low concentrations to produce substances that can be detected by their odor, and it is very likely that the undesirable tastes and odors encountered in chlorinated surface waters owe their characteristics to such phenomena. It is definitely known that some organic materials, such as phenol, react with chlorine to create undesirable tastes and odors in extremely small concentrations.

Ozone and ultraviolet light are both effective agents for the killing of pathogenic bacteria that may be present in water; however, neither one has been seriously considered in the U.S. because of high cost and the unavailability of well-designed equipment to apply these agents. These agents have been used in Europe. If ozone could be used, it would have some practical advantage over chlorine in that it would oxidize many of the compounds that have a disagreeable taste and odor. There are many who believe that ultraviolet light is effective because it produces ozone or hydrogen peroxide. If this is the case, it may be practical at some future date to sterilize water with ozone or hydrogen peroxide when they become available at a relatively low cost.

Removal of Taste and Odor. Disagreeable odors and tastes may be introduced into the water supply from a number of sources. Industrial waste and sewage may occasionally contain phenols and oils that can impart objectionable taste, particularly after chlorination. Some organisms, such as algae, streptomyces, and some protozoa, can produce oils and cyclic organic compounds that may have a taste and odor in themselves which become more intense after chlorination. Decaying organic matter, either from sewage or vegetation, can leave end products that impart a bad taste and odor, and these also can be amplified by chlorine. The production of potable drinking water may, therefore, require special care of the supply and modified treatment in the purification plant.

Excessive growth of algae in reservoirs can be controlled by treatment of the water with copper sulfate. If this is not used in excessive amounts, it will not injure the water because the amount of copper required for the destruction of most algae is considerably below the amount that is toxic to animal life. In some places it has been found desirable to prechlorinate the water before adding the coagulating chemicals so as to kill some of the organisms that may be responsible for taste and odors. The killed organisms are more easily removed by the coagulating chemicals than the live ones, and if they are not removed in the settling tanks with the floc, they will be carried on to the sand filters where they get caught by the sand and eventually die

and disintegrate, and liberate the compounds responsible for the taste and odors. The raw or untreated water will contain more organic matter than the finished water and, therefore, more chlorine will be needed in this prechlorination than in the post chlorination.

It has been found that ordinary water softening will often remove many of the compounds that are responsible for taste and odor. While it may not be possible to justify this added treatment as a means of controlling taste and odors, it certainly is an argument in favor of softening when contemplated for other purposes. See p. 931.

Activated carbon has been found to be a rather effective agent for removal of taste and odors as well as color, and in some communities it has been found desirable to add activated carbon to the settled water just before it reaches the sand beds, or to filter the water through beds containing activated carbon before it is put on the sand beds. The high cost of such treatment is a deterrent for more intensive application.

A method of applying chlorine developed about 1939 (5,7), called the "*break point*" method, appears to overcome some of these tastes and odors developed by chlorine. To explain the principles that are involved it is necessary to discuss briefly some of the chemistry concerned. If one adds a given amount of chlorine to a sample of water and then waits a few minutes and determines the amount of available chlorine that is left, it is generally found that the available chlorine will be less than the amount added. The difference is due to the chlorine that has been used in oxidizing some compounds present. On adding varying amounts of chlorine to a series of samples of water and determining the amount of available chlorine left in each sample after a few minutes, it is possible to plot a curve, showing how the available chlorine increases with the increments of chlorine added. Such a curve will generally continue in a straight line until a certain point is reached, referred to as the break point, after which, with an additional increment of added chlorine, it is found that there is a decrease in the available chlorine. After this has occurred, an additional increment of chlorine will again bring about an increase in the available chlorine. After the break point, however, the increase in available chlorine after each increment will agree fairly well with the amount of the added chlorine. The reason for this peculiar behavior is that when the chlorine reaches a high enough concentration, it can oxidize compounds that hitherto resisted oxidation. Many of these are the ones that cause tastes and odors. It has been found that, in water that has been chlorinated beyond the break point, undesirable tastes and odors are, to a large extent, eliminated. The amount of chlorine required to reach a break point may, in many instances, be greater than that necessary for disinfection and, in fact, may be too much chlorine to carry in the distribution system. When excessive amounts have to be added to reach the break point it is then necessary to remove the excess by dechlorination. Appropriate dechlorinating agents are such chemicals as thiosulfate, sulfite, or other sulfur compounds that react quickly with available chlorine.

Care of Distribution System. In order to be certain of delivery of healthful and potable water to all consumers on a distribution system, it is necessary for the individuals who operate the water treatment works to maintain diligence and make frequent inspections of the distribution system. Samples of the water should be taken at different points in the system at frequent intervals to make certain that the water meets the standards of purity when it reaches the consumer and that the residual chlorine is high enough to serve as a protection in case of accidental contamination. Such care is necessary because it is possible for recontamination of the water supply

to take place after it leaves the treatment works. Some industries may have water supplies of their own, usually from wells, and if the piping from this is interconnected with the city supply, the local supply can become contaminated from a contaminated well. There have been many cases where cross connections have been found in certain buildings between the waste system and the water supply system, so that under conditions of low pressure it was possible to get a flow from the sewage system into the water system. In other cases where there may be breaks in the piping of the distribution system, it is possible to get contamination from contaminated soil through which the pipes pass, when there is a lowering of pressure within the distribution system because of emergency use of water. Because of the possibility of this type of contamination, it is necessary to maintain a residual of chlorine throughout the entire distribution system, and have frequent inspections in order to try to find cross connections wherever they may occur. Municipalities should also protect themselves by local laws and ordinances prohibiting interconnection of local water supplies with muncipal water supplies. There should also be ordinances governing plumbing installation so as to avoid possible cross connections between sewage systems and water supply systems.

There are a number of different kinds of nonpathogenic organisms that can grow in the pipe lines of the water distribution system, particularly some of the *Chlamydobacteriales*. If the growth of these becomes excessive, they may also impart tastes and odors to the water. Growth of such organisms may also be facilitated if the water supply contains an excessive amount of iron or manganese. If the growth of such organisms is extensive, they may form a heavy slime coating in the pipes, and at the base of this slime, conditions become anaerobic, so that anaerobic bacteria may flourish. This not only is undesirable in itself, but, to make water matters worse, some of these organisms can reduce sulfate to produce sulfide and thus impart a hydrogen sulfide odor to the water. Eliminating this type of difficulty may involve a more careful control of the chemical characteristics of the water and may necessitate frequent flushing of the pipe line, especially in dead end areas where the water is likely to stand for some time and become stagnant.

Bibliography

(1) American Public Health Assoc. and American Water Works Assoc., *Standard Methods for the Examination of Water and Sewage*, 9th ed., N.Y., 1946.

(2) American Water Works Assoc., *Water Quality and Treatment*, N.Y., 1940.

(3) Buswell, A. M., *The Chemistry of Water and Sewage Treatment*, Chemical Catalog Co., N.Y., 1928.

(4) Fair, G. M., and Geyer, J. D., *Water Supply and Waste-Water Disposal*, Wiley, N.Y., 1954.

(5) Farber, H. A., "Super-Chlorination Practice in North America," *J. Am. Water Works Assoc.*, **31**, 1599 (1939).

(6) Frobisher, M., Jr., *Fundamentals of Bacteriology*, 5th ed., Saunders, Philadelphia, 1953.

(7) Griffin, A. E., and Chamberlin, N. S., "Some Chemical Aspects of Breakpoint Chlorination," *J. New England Water Works Assoc.*, **4**, No. 3, 371–83 (1941).

(8) Henrici, A. T. (rev. E. J. Ordal), *The Biology of Bacteria*, 3rd ed., Heath, Boston, 1948.

(9) Hoover, C. P., *Water Supply and Treatment*, 7th ed., National Lime Assoc., Washington, D.C., 1951.

(10) Laux, P., "Break Point Chlorination and Taste and Odor Control," *Taste Odor Control J.*, **9**, No. 11 (1943).

(11) Levine, M., "Bacteria Fermenting Lactose and Their Significance in Water Analysis," *Iowa State College Agr. Bull.*, **62** (1921).

(11a) *Livre de l'Eau*, Vol. I, Centre Belge d'Étude et de Documentation des Eaux, Flemalle-Grande (Belgium), 1954.

(12) Nordell, E., *Water Treatment for Industrial and Other Uses*, Reinhold, N.Y., 1951.
(13) Orchard, W. J., "Break Point Chlorination for Taste Control," *Eng. News Record*, **124**, 521–22 (1940).
(14) Prescott, S. E., Winslow, C. E. A., and McGrady, M. A., *Elements of Water Bacteriology*, 6th ed., Wiley, N.Y., 1946.
(15) Smith, G. M., *Fresh Water Algae of the United States*, 2nd ed., McGraw-Hill, N.Y., 1950.
(16) Thresh, J. C., and Suckling, E. V., *Examination of Waters and Water Supplies*, 5th ed., Blakiston, N.Y., 1943.
(17) Ward, H. B., and Whipple, G. C., *Freshwater Biology*, Wiley, N. Y., 1918.
(18) Welch, P. S., *Limnology*, 2nd ed., McGraw-Hill, N.Y., 1952.
(19) Whipple, G. C. (rev. G. M. Fair and M. C. Whipple), *Microscopy of Drinking Water*, 4th ed., Wiley, N.Y., 1927.

H. O. HALVORSON

WATER ANALYSIS. See *Water (municipal)*.

WATER GAS. See *Manufactured gas*, Vol. 8, p. 783.

WATER GLASS. See *Silica and silicates (soluble)*, Vol. **12**, p. 303.

WATERPROOFING AND WATER REPELLENCY

Textiles ..... p. 962
Paper 975
Leather ..... p. 976
Concrete and Masonry 977

Waterproofing treatments are applied to a great diversity of products ranging from clothing to building structures, including such varied materials as textiles, paper, leather, cement, and masonry. Strictly speaking, the term "waterproofing" denotes a process that confers complete impermeability to the passage of water, but it is also used in a general sense to include water-repellency (nonwetting) treatments which produce porous hydrophobic surfaces without appreciably changing the original texture and pore structure.

Textiles

The literature of water-resistant treatments of textiles is probably as extensive as that of any other finishing process. Early patent literature is cited in the books of Mierzinski (35) and Pearson (43). A review of "chemical methods" only for imparting water repellency contains 332 references (47), while a bibliographical survey of the field from 1937 to 1947 (22) contains 250 references. Sixty-four PB (Publication Board) reports, received from both domestic and foreign, civil and military agencies, are cited in the suggested list of references on water repellency and waterproofing of textiles issued in 1950 by the Office of Technical Services, U.S. Department of Commerce (58). The number of products offered on the market for application to cloth probably exceeds a hundred. See also *Coated fabrics*; *Textile technology*.

Terminology. Much confusion prevails in the use of terms pertaining to waterproofing processes and resulting products. The need for clarification has been expressed by most writers on the subject (26,31,35,43,46), and several technical and government agencies have proposed definitions in an effort to accomplish this purpose.

In the Technical Manual and Yearbook of the American Association of Textile Chemists and Colorists (1) are the definitions: *water resistance (fabric)*—a general term denoting the ability of a fabric to resist wetting and penetration of water; *water repellency (textile)*—the ability of a textile fiber, yarn, or fabric to resist wetting. In A.S.T.M. standard D583–54 (2) are essentially the same definitions except that the term *water resistance* is used in a less restricted sense to denote the "ability of a fabric

to resist wetting or penetration or both." The Commodity Standards Division, U.S. Department of Commerce, has been working for several years to establish a commercial standard with test methods and ratings for "Water Repellent Textile Fabrics for Outerwear," (57) as a basis for better understanding between buyer and seller. The Federal Trade Commission has been working along similar lines on "Proposed Trade Practice Rules Respecting Use of 'Waterproof,' 'Rainproof,' 'Water Resistant,' and Similar Designations as Descriptive of Outerwear, Fabrics for Outerwear, and Compounds or Treatments Therefor" (61).

Although the term *waterproofing*, as used here, is commonly applied in a broad sense to all types of treatments for rendering textiles resistant either to the passage of water through them or to wetting by contact, the present tendency is to limit its application to the production of coated and impregnated fabrics that are highly impervious to water in both the liquid and vapor states. The term *water-repellent treatment* is then applied to those processes that produce a hydrophobic surface, characterized by high resistance to wetting. Such surfaces are usually highly permeable to water vapor and air, and they may or may not be highly resistant to the passage of liquid water under pressure.

Use of the term *waterproof* is generally discouraged because nothing is really waterproof in the truest sense of the word. However, for want of a better descriptive term to connote high resistance to penetration, and to distinguish between porous and nonporous surfaces, it is often applied in a purely relative sense to highly impervious fabrics produced by any means whatsoever. In this sense, it is applicable also to untreated fabrics such as heavy ducks, Ventile, and other swellable or dense fabrics which owe their resistance to tightness of the weave and swelling ability. Such fabrics possess little resistance to surface wetting unless they have been given a water-repellency treatment.

In contrast to the "waterproof" impervious wall-like structure is the *water-repellent* surface which is resistant to the spreading of water on its surface and to wetting by raindrops. *Spot-resistant* and *stain-resistant* surfaces are similar but resistant to a lesser degree, for they are primarily intended to prevent deposition of water-borne soiling agents. Their protective action does not apply, however, for grease, organic solvents, or water to which surface-active agents have been added.

The term *water resistance* is a convenient general term for covering all aspects of resistance to water, individually or collectively, and including resistance to penetration of water, wetting of the surface, and absorption. Under other conditions than those discussed here, it even covers resistance to damaging effects caused by water.

Other terms often encountered are *permeable* or *pervious-to-air and water-vapor*, and *porous*, to distinguish fabrics said to "breathe" from their relatively impenetrable counterparts described in opposite terms

The terms "*durable*" and "*nondurable*" (also called *renewable* or *retreatable*) are applied to repellents and finishes to differentiate between those that are designed to withstand cleaning processes (durable) and those that must be re-applied (nondurable) after dry cleaning or laundering.

From this discussion, it obviously follows that there is real need for setting up a definite terminology in the waterproofing industry but that, for the present, the meaning of terms must be explained by those who use them.

IMPERMEABLE FABRICS

The majority of the textiles made resistant to the passage of water by man are used to keep him or his property dry. When the textile is not to be worn—as a tent

or a tarpaulin—coated impermeable fabrics are often satisfactory and generally more economical. In these cases, waterproo..ng is accomplished by filling the pores of the fabric with materials such as oils, varnishes, pigments, rubber, plastics, tar, and many other materials that interpose a physical barrier to prevent water from passing through.

The impregnating material is sometimes modified so that several benefits may be derived from one application. For example, chlorinated paraffin may be substituted for paraffin to contribute toward flame resistance as well as water resistance of a fabric. An example of such multipurpose treatment is used in the Army's "fire, water, weather and mildew resistant duck" (56).

Dean (13) has described a simple waterproofing treatment for canvas, suitable for home application, which also gives some measure of protection against mildew and sunlight by incorporation of copper naphthenate and pigments with the waterproofing material. A typical formulation specifies 8.5 lb. petroleum jelly, 1.5 lb. beeswax, 5 lb. dry earth pigments (such as ocher, sienna, or umber) 1.5 lb. copper naphthenate (10% Cu), and 5 gal. of mineral spirits. A pound of lampblack may be substituted for the earth pigments and 7.5 lb. medium hard asphalt together with 2.5 lb. of petroleum jelly may be substituted for the petroleum jelly–beeswax mixture. The materials are dissolved or mixed in the open with great care to be sure no flame or sparks are near. The solvents may be warmed by placing the containers in a tub of hot water. The mixture is somewhat poisonous, and due precautions should be observed. The well-stirred mixture can be applied to canvas with a paint brush. Lighter fabrics may be soaked in the solution, diluted with mineral spirits, and then the cloths can be wrung out and dried. The hands should be protected from contact with the liquid as far as possible.

The early "oilskin slickers" lost popularity because of their weight, stiffness, and general lack of comfort. Some of the newer coated fabrics used in the manufacture of rainwear have the advantage of extreme lightness and flexibility, but are almost as impermeable to air as they are to water. Thus, because of inadequate ventilation, the wearer may become almost as wet from perspiration as he would be from rain without the coat.

Another type of impermeable cloth, called "self-sealing" fabric, is exemplified in tightly woven tentage, water bags, and linen fire hose. For example, fire hose is woven from low-twist linen yarn which has low elongation. The fibers wet readily and then expand with the absorbed moisture to give a tightly packed structure with little stretchability which resists leakage under water pressure. Untreated cotton fibers tend to make a less favorable type of yarn structure for self-sealing. However, in England, Peirce *et al.* (68) produced a cotton fire hose, and further development gave a fine light-weight fabric of Oxford weave which was produced under the name of "Ventile" cloth. Some work on self-sealing fabrics at the Southern Regional Laboratory in the U.S. has been reviewed by Reid and Goldthwait (44) and includes; (*1*) the addition of hydroxyethylcellulose to the fibers as a permanent finish which swells when wet, thus preventing passage of water (19), (*2*) the use of fine, immature cottons to obtain better closing, and (*3*) the use of a special loom attachment to greatly increase the number of picks per inch (34). Although the self-sealing fabrics ordinarily require wetting to resist further passage of water, they are essentially impermeable to air or to large amounts of water after wetting. A certain amount of seepage occurs, of course, but this is often beneficial. In the case of fire hose, it protects the fabric from burning, and with water bags, evaporation keeps the contents comfortably cool. In modern practice some self-sealing fabrics are given an additional chemical treatment to make the fibers water-repellent.

WATER-IMPERMEABLE–WATER-VAPOR-PERMEABLE COATED FABRICS

An entirely new type of water-resistant fabric has been developed in work done for the U.S. Department of the Army (33) in that a coated fabric that is both permeable to water vapor and impermeable to water has been originated. This fabric is produced by incorporating a solid pigment into a synthetic rubber binder in such manner that a network of three-dimensional microscopic pores is produced. This material may be coated on one or both sides of a water-repellent cloth to give a coated fabric that has been found to withstand more than 277 cm. of water pressure by a modified Suter test but that will also transmit at least 75% as much moisture vapor as the original fabric.

In explanation of the theory of this new fabric, an illustrative example is given: 100 g. of a pigment of specific gravity of 2.70 was found to occupy 127 cu.cm. as compared to a theoretical volume of only 37 cu.cm. This meant that 90 cu.cm. of void space was available. If 50 cu.cm. of binder were used to hold these particles together, 40 cu.cm. or about 31.5% of the coating, would consist of voids available for transfer of moisture vapor. It was found that for the same pore area, moisture vapor transfer was not greatly affected by the size of the pores but hydrostatic head was greatly influenced at sizes smaller than 30 microns.

Although coatings containing porous pigments were satisfactory with regard to water-vapor permeability and resistance to hydrostatic pressure, they were not so satisfactory with respect to flexibility, flex resistance, aging resistance, and washing and/or dry cleaning. However, by using a solid pigment bound with an oil-resistant synthetic rubber, a product was obtained that was satisfactory in all respects except that it resisted a hydrostatic head of only about 100 cm. This was improved by incorporation of a wax into the rubber to increase its contact angle. By bleeding into the surface, the wax increased the contact angle, decreased pore diameters, and improved resistance to aging. When a 4–5 oz. fabric, coated with from 4 to 5 oz. per square yard of solid pigment–solvent cement binder, was made into suits, and tested for comfort on Army personnel, the material was considered highly satisfactory.

WATER-REPELLENT FABRICS

Theory. The discomfort entailed by the wearing of impermeable fabrics has led to the development of fabrics that repel water but are permeable to both air and water vapor. These fabrics have been treated with a chemical so that the individual fibers repel the water and cause it to collect in drops on the surface and to run off instead of penetrating the yarns. The interstices between the fibers and yarns remain essentially unchanged, thus allowing the ventilation necessary for body comfort, but the surface tension of the water droplet prevents it from breaking up and going through the holes.

The theory of water repellency has been reviewed in considerable detail by Baxter and Cassie (6) and also by Rowen and Gagliardi (46). It was pointed out that when a drop of water touches a solid it may form an almost perfect sphere in the case where it does not wet the surface, or it may flatten and completely cover the surface if it wets it. The tendency of a solid to resist wetting is a function of the chemical nature of the solid surface, the presence of other molecules adsorbed on this surface, the roughness of the surface, and the porosity of the surface. When these factors are applied to a consideration of textiles, it is apparent that the hydrophilic surface characteristic of

most textile fibers must be eliminated and also that fabric and garment structure are very important.

The presence of other molecules on the surface of the solid is important in practical considerations of the water-repellency of fabrics. Dirt, dust particles, greasy soil, residual soap after cleaning, and the like all affect the shape of the water drop. Also, impurities in the water itself which lower the surface tension enable the water to wet the fabric. The addition of wetting agents to water enables it to penetrate and wet almost any commercially treated water-repellent fabric (49). Both roughness and porosity of the surface affect wettability of the fibers. The principles involved have been applied to the postulation of an ideal fabric (6), and it is shown that a duck's feathers admirably satisfy the theoretical requirements.

Garment design as well as cloth design is important. The effective resistance of two adjacent layers of water-repellent fabrics is many times that of either layer by itself. This is illustrated in Table I by Sookne (52) which shows time of water penetration under various conditions.

TABLE I. Comparison of Rainfall Resistance of a Single and Double Layer of Cotton Poplin Fabric.

Condition	Resistance of cotton poplin to rainfall, sec.	
	Single layer	Double layer
No water-repellent treatment	6	8
Slight water-repellent treatment	15	44
More water-repellent treatment	40	700
Better water-repellent treatment	51	8,500
Best water-repellent treatment	65	10,000

The greatly increased efficiency of two layers is attributed to the fact that a double layer affords greater energy absorption under impact; furthermore, a very low order of probability exists that two holes in the fabrics will coincide so as to form a continuous path for the raindrop.

It has also been reported (51) that the supporting surface markedly affects the water resistance of water-repellent cloth. Thus, it may be necessary for coat linings to be made water repellent. Finally, the sewing thread used in raincoats must also be made water repellent to prevent the garment from leaking at the seams in heavy rain.

General. The principal commercial processes are discussed under the following headings: metal salts and oxides; proteins and other nitrogenous compounds; esterification and etherification reactions of cellulose; silicones.

Details of application are easily obtained from manufacturers' bulletins, but the exact composition of the various formulations offered is often a trade secret. However, after World War II, an extensive survey was made of the German chemical developments in improving the water resistance of textiles (11) and detailed formulas have been published on many of the German processes. German effort was aimed mainly at rayon treatment, and it is stated that the wax–aluminum salt nondurable treatments are conventional except for the substitution of zirconium oxychloride for aluminum salts. In the durable repellent field, treatments were developed (Persistol VS and Persistol KF) which, although quite different from the long-chain pyridinium complexes commonly used in the United Kingdom and in the U.S., were claimed to be even more resistant to laundering. These are described on pp. 970–71.

A number of general precautions are necessary in the application of water-re-

pellent agents to cloth (21,51). First, the cloth must be selected with considerable care both as to composition and construction. At one time cotton and wool garments were the only ones treated, but with advances in the use of synthetic fibers, nylon, viscose rayon, acetate, and other synthetics are also used for rainwear. The effect of construction and garment design has already been mentioned.

Secondly, the cloth must be carefully freed from natural impurities, residual finishing agents, and other chemicals such as starch size, alkalies, and soaps prior to treatment with the water-repellent agent.

Thirdly, the cloth must be thoroughly impregnated particularly when durable repellents are used. The assistance of wetting agents is not feasible in many cases since residual amounts counteract the water-repellent effect.

Finally, the effect of other finishing agents applied with the water-repellent agent may lower the repellency. Water-repellent agents are sometimes used in conjunction with other finishing agents to give special effects.

Metal Salts and Oxides. One of the earliest methods of producing water-repellent cloth involved the precipitation of basic aluminum acetate of varied and indefinite composition within the fibers. In one process (32,35,43) an aluminum acetate solution was prepared by the double decomposition of a 9% solution of aluminum sulfate with a 14% solution of lead acetate. Cloth was then impregnated with the solution and rolled up wet without squeezing. This was repeated 4 times and the cloth dried by moderate heat in a festoon chamber. In another process the aluminum acetate was treated with alkali so that alumina was produced to make the cloth water-repellent.

The use of soap instead of alkali to precipitate the aluminum was an obvious step and the presence of an aluminum soap, mostly aluminum stearate, greatly improved the product. This process in modified form has continued in use to the present day. It is best carried out as a two-bath process, in which case it is better to apply the soap first to be sure that all the soap has reacted since residual soap will counteract the water-repellent effect. Cloth is impregnated with a 1% solution of soap, squeezed, and then worked in a jig with a 5% aluminum acetate solution. The cloth is then dried. In an alternative one-bath method, the aluminum soap may be applied from an emulsion as such or the components may be emulsified together, the reaction to form the soap taking place when the cloth is dried. The aluminum soap may also be dissolved in Stoddard solvent (see Vol. **10,** p. 167) or in benzene and applied from the solution, but this process involves the usual disadvantages of using flammable organic solvents.

Paraffin wax, emulsified with aluminum acetate or formate for use in one-bath treatments, is often employed at the present time. In 1954 it was estimated (7) that the nondurable treatments of this type dominated an estimated $5–8 million market but that durable treatments involving use of quaternary pyridinium complexes and silicones (see below) were gaining ground rapidly. Among the commercial products reported to contain wax emulsions with aluminum salts are Ramasit (General Dyestuff), Migasol (Ciba), Niaproof (Carbide and Carbon), Impregnole and Norane W-1 and W-2 (Warwick Chemical), Aridex (Du Pont), Arcopel DC-2 and DC-3 (American Resinous Chemicals), Cravenette-renewable type (Cravenette Co.), Paramul Repellent 115, DC-1 and DC-2 (American Cyanamid), as well as many others.

In one variation of the paraffin wax–aluminum salt method (50), a protective colloid such as gelatin or polyvinyl alcohol is added to the emulsion. This emulsion

may be dispersed in hot water to give a stable acidic emulsion bath. The emulsion particles are strongly cationic and tend to exhaust somewhat onto cellulosic fibers and almost completely onto wool. Add-on is regulated to about 5%. On drying at about 105–115°C., the acetic or formic acid volatilizes and leaves a hydrated aluminum oxide together with a fused wax coating on the fibers. A similar one-bath emulsion can be prepared without the protective colloid to yield a softer hand. However, it is necessary to add the aluminum salt solution to the paraffin emulsion at about 80°C. in order to prevent precipitation; the emulsion may then be cooled and applied as desired. Although the finish will withstand weathering fairly well, it is removed by laundering or dry cleaning.

The use of zirconium in place of aluminum assumed importance in Germany during World War II and has since been used to some extent in the U.S. Application methods are identical with those just described for aluminum but the fabrics so treated, particularly wool and rayon, will retain a considerable amount of water repellency after several dry cleanings or launderings. Zirconium oxychloride, $ZrOCl_2$, is often used and this must be buffered with sodium acetate to prevent tendering of the cloth due to evolution of hydrogen chloride when the oxychloride hydrolyzes. The superiority of the zirconium compounds over those of aluminum is ascribed to differences in solubility. White (70) has pointed out that zirconium stearate is only slightly soluble in dry-cleaning solvents and that it is also highly resistant to caustic. Aluminum soaps dissolve in caustic, whereas the zirconium soap, if attacked, is converted to insoluble hydroxides or carbonates of zirconium. The use of the rare earth soaps, as well as those of thorium, zirconium, and uranium, has been patented (70).

The use of tetraalkyl orthotitanates, where the alkyl may range from ethyl to octyl, has been suggested for making cloth permanently water-repellent but these compounds are not known to be used commercially (53).

One of the newer metal salts employed commercially is "stearatochromic chloride" (approximately hydroxostearatodichromium(III) chloride, $[Cr_2(OH)C_{17}H_{35}COO]Cl_4$ (23,71) (Quilon, Du Pont). It is reported that this compound is used to treat about half of the fur felt hats made in the U.S., also that it is being applied to paper, glass-fiber window drapes, and various clothing fabrics (6,50). The compound is a Werner complex which attaches to the fiber surfaces by nonionic coordination linkages. When the cationic solution is applied to the textile and heated to about 120°C., the compound hydrolyzes and then dehydrates, forming a chelate ring which holds the organic portion of the molecule in an oriented position to the surface to give water repellency.

Proteins and Other Nitrogenous Compounds. Proteins have been used extensively to give water-repellent finishes. Solutions of proteins such as glue were insolubilized with aluminum compounds or formaldehyde, tannin, or dichromates. Marsh (32) reviews a number of patents on the use of proteins, and Harding (21) states that the "Mystolenes" manufactured in the United Kingdom are protein-aluminum complexes. Glue is used in many formulations (11).

The use of condensation nitrogen-base resins as the basis of, or in conjunction with, water repellents has increased. The Permel Plus Finish of the American Cyanamid Co. is reported (6) to be Permel (otherwise unidentified) combined with a melamine- or urea-formaldehyde condensate. Morel (37) has described two treatments using urea-formaldehyde resins. A number of water repellents, including the silicones described below, are reported to be compatible with the nitrogenous resins used for creaseproofing. Some are reported to contain stearamide. The nitrogen resins have

been used for a number of years to impart wet-strength to paper. (See under "Paper," p. 975.)

Nitrogen-containing compounds which are assumed to etherify cellulose are considered in the following section.

Esterification and Etherification Reactions of Cellulose. The idea of combining a water-repellent group with cellulose by chemical reaction—for example, replacing the hydrogen of a hydroxyl group with a long-chain compound—is one that has intrigued many investigators of textile treatments. The special advantage of such a process would be the relatively stable character of the resultant compound, but the obvious difficulty has been carrying out such reactions in an economical manner for commercial exploitation.

The reactions of cellulose are mainly esterifications or etherifications. Schuyten *et al.* have reviewed a large number of such reactions claimed to give water repellency (47). See also *Cellulose derivatives.*

Examples of *esterification* include the formation of a partially substituted cellulose ester such as the stearate made by the use of stearic anhydride or stearoyl chloride. Substituted ketenes and long-chain isocyanates (see Vol. **10,** p. 398) that might add directly to the cellulose have been suggested. Hamalainen *et al.* (20) found that *n*-octadecyl isocyanate imparted only mild water-repellent properties to cotton textiles and suggest that much of the water-repellent effect may be due to decomposition of the octadecyl isocyanate to yield a waxlike coating of dioctadecylurea rather than to a true reaction with the cellulose. Such processes do not appear promising for commercial use.

It is in the field of cellulose *etherification* that most progress has been made along the lines of developing durable water repellents. Cellulose ethers as a class are stable toward alkali and, therefore, finishes made by formation of ethers are durable toward laundering. The historical development of the water-repellent ethers has been reviewed by Marsh (32). Briefly, from 1931 to 1937 a number of materials were produced to give cotton a softer hand or improve its dyeing characteristics. These compounds were designed to react with cellulose to form an ether through the agency of a chloromethyl group. Reynolds, Walker, and Woolvin, in 1937 (66), modified the method to produce durable water repellency using compounds such as 1-(octadecyloxymethyl)pyridinium chloride to react with the cellulose. With a number of modifications (67) this process is the basis for the compounds known in England as Velan and in the U.S. as Zelan. These are considered to be mainly stearamidomethylpyridinium chloride, although 1-(octadecyloxymethyl)pyridinium chloride is also used (21).

Stearamidomethylpyridinium chloride may be prepared by heating stearamide with paraformaldehyde and pyridine hydrochloride in solution in pyridine (67). Some of the reactions of this compound with alcohols and the formation of various stearamidomethyl ethers have been investigated by Weaver *et al.* (63):

$$[C_{17}H_{35}CONHCH_2NC_5H_5]^+ Cl^- + ROH \longrightarrow C_{17}H_{35}CONHCH_2OR + HCl + C_5H_5N$$

While the compounds formed are ethers, they do not possess the stability of the usual ethers because of the presence of the —CONH— group. For example, the amidomethyl ethers may be split by dilute aqueous solutions of strong acids.

This work has been further amplified (48) and applied to the reaction with cellulose where R in the above formula indicates a cellulosic residue attached to the hydroxyl group. Davis (12) had investigated the possible reaction of stearamidomethyl-

pyridinium chloride with cotton and concluded that about 1–2% would react with cellulose to form the ether. He proposed that the mechanism involved hydrolysis to form methylolstearamide (*N*-(hydroxymethyl)stearamide), $C_{17}H_{35}CONHCH_2OH$, which then reacted with cellulose. In the later investigation (48), the workers agreed with the amount of reaction but found that methylolstearamide would not react with cellulose under the conditions of curing. They believe that the reaction as given above takes place to the extent of about one substituent for every 150 anhydroglucose units of the cellulose. They also point out that the conditions of curing during application of the compound to textiles favor the formation of distearamidomethane (*N*,*N*′-methylenebisstearamide), $(C_{17}H_{35}CONH)_2CH_2$. This compound is deposited on the fibers and aids greatly in giving good water repellency. It is somewhat resistant to laundering, but the textiles made water repellent by distearamidomethane alone require ironing after laundering to recover their water repellency. Probably the wax-like material must be melted and redistributed on the fiber surface after the disruptive swelling effect of the laundering.

Commercial application of water repellents of the stearamidomethylpyridinium chloride type varies with the particular product, and a number of competitive products are on the market. A typical product has been described (48) to be a paste composed largely of stearamidomethylpyridinium chloride. The paste is applied to the fabric in from 2 to 6% pickup, based on the weight of the fabric, the amount varying according to the properties of the individual fabric. It is used on cotton, linen, viscose rayon, cellulose acetate, nylon, acrylic fibers, silk, and wool. The paste is first dissolved in about half of the water to be used at about 40°C., using good mechanical stirring to disperse it. About 10% of the weight of the paste of anhydrous sodium acetate is separately dissolved in warm water and added. The whole is then made up to volume with more water. The sodium acetate is very important to the success of the treatment since it serves to buffer the solution and neutralize the hydrogen chloride evolved during the reaction and thus it protects the cloth from tendering. The buffered solution is slightly acid and this acidity must be maintained during application. The opalescent solution is stable for only a few hours and should be applied to the cloth fairly soon at about 40°C.

The solution is impregnated into the cloth and excess solution squeezed out by passing the cloth through rubber squeeze rolls to leave the desired pickup. After the cloth is dried at 66–160°C., the object being to remove the water but not to decompose the compound, it is cured at 135–200°C., the optimum temperature varying from about 177°C. for cotton and linen to about 150°C. for the synthetic fibers. Curing times vary inversely with the temperatures used, and conditions are usually established experimentally for a given fabric and equipment. During curing, part of the agent reacts with cellulose to give the cellulose ether and part decomposes to yield distearamidomethane.

Fumes of formaldehyde and pyridine are given off from the padding baths and on drying and curing the cloth. Therefore, good ventilation must be provided at all points. The fumes are slightly acid, so acid-resistant materials must be used in the equipment. The cloth is also slightly acid at this point and contains residual decomposition products of the reaction. It must be neutralized, for example with small amounts of soda ash solution, and thoroughly washed. The cloth is then dried at the highest practicable temperature (135–175°C.) to develop maximum repellency.

1-*n*-Octadecyl-1′-ethyleneurea, developed as "Persistol VS" in Germany, was

claimed to be superior to Velan PF on rayon. Details of its preparation and use are given by Dahlen and Pingree (11). The repellent agent was prepared by treating *n*-octadecyl isocyanate with ethylenimine in emulsion:

$$C_{18}H_{37}NCO + NH.CH_2.CH_2 \longrightarrow C_{18}H_{37}NHCON.CH_2.CH_2$$

This compound is claimed to react with cellulose ($R_{cell}OH$) on drying at about 80°C. to give the corresponding ether:

$$C_{18}H_{37}NHCON.CH_2.CH_2 + R_{cell}OH \longrightarrow C_{18}H_{37}NHCONHCH_2CH_2OR_{cell}$$

A small amount of a reagent capable of cross-linking the cellulose was also added. For this, compounds such as 3,3′-diethylene-1,1′-hexamethylenediurea, CH_2CH_2N-$CONH(CH_2)_6NHCONCH_2CH_2$, were used.

Silicon Compounds. In 1942 a patent was granted to Patnode (72), and assigned to the General Electric Company, on the use of vaporized methylsilicon chloride (methyltrichlorosilane), CH_3SiCl_3, for treating various materials including paper, cotton cloth, and ceramics to render them water-repellent. With this patent a new type of water-repellent agent was introduced. Until that time, most repellent agents had depended upon a long hydrocarbon chain for efficacy, whereas the silicon compounds needed only methyl groups attached to the silicon molecule to prevent wetting. Most of the methyl silicones now on the market are made up of relatively long chains of silicon and oxygen atoms to which are attached the methyl groups, which are hydrophobic and prevent wetting. See *Silicon compounds (organic)*, Vol. **12,** pp. 365–92; *Silicones,* Vol. **12,** pp. 393–414.

Methylsilicon chloride did not prove practical for use on cotton textiles because the by-product, hydrogen chloride, tendered the textile. Barry (73) produced long-chain silicon acetates which gave water repellency without production of harmful strong acids. Eventually, silicone resins were found suitable for this purpose. The physical state of these compounds may be varied from low-viscosity fluids to rubberlike solids with suitable variation in the substituents and the degree of polymerization. The three largest producers are the Dow-Corning Corporation, General Electric Company, and Linde Air Products Company. A review of the field in 1954 (6) states that the first large use of silicone resin water repellents was in 1950 but that the use is expanding very rapidly.

The silicones are produced by hydrolysis of alkylsilicon chlorides (alkylchlorosilanes) and polymerization of the resulting silanol. A typical reaction may be expressed as follows:

$$3\,(CH_3)_2SiCl_2 + 6\,H_2O \longrightarrow 3\,(CH_3)_2Si(OH)_2 \longrightarrow HOSi(CH_3)_2OSi(CH_3)_2OSi(CH_3)_2OH$$

By-product hydrogen chloride is removed and thus the use of the silanols eliminates the problem of acid tendering. Presumably further polymerization occurs on the cloth during curing so that the silicone becomes insoluble and good resistance to laundering and dry cleaning is obtained.

Application of the silicones to cloth may be either from organic solvents or from aqueous emulsions, and examples of both are numerous in the patent literature. Some of the commercial products require a metallic salt catalyst and some do not. In general, curing at a fairly high temperature such as 155°C. for 4–8 minutes is required in order to complete the polymerization of the silicone and to make the product durable

toward laundering and dry cleaning. A typical example of an agent (74) claims water repellency if a mixture of 20–70% of a liquid methyl polysiloxane is used with a mixture of 80:30 of a liquid methyl hydrogen polysiloxane.

The silicones are claimed to give a number of desirable properties to the fabrics in addition to durable water repellency. It is said (14,18) that on cellulose acetate fabrics the silicone completely covers the individual fibers and that the wrinkle recovery, abrasion resistance, tear and bursting strength, sewability, and appearance are all significantly improved by less than 2% add-on of silicone resin.

Most of the preparations of water-repellent silicone resins on the market are compatible with the creaseproofing resins of the urea- or melamine-formaldehyde type, and it is even claimed that enhanced water repellency is obtained with such resins (75). In an example cited, one part of an organopolysiloxane such as methyltris(trimethylsiloxy)silane, $CH_3Si(OSi(CH_3)_3)_3$, is mixed with about one-fourth part of the hydrolyzate of methyldichlorosilane, CH_3SiHCl_2, and with a precondensate of a melamine resin. When applied to cloth, dried, and cured for 2 minutes at 150°C., the product is claimed to be water-repellent.

Typical instructions with one commercial silicone product suggest that the silicone be emulsified to 40% concentration in a colloid mill using emulsification agents that will not cause back-wetting. This master solution may be diluted to 2% for application to the cloth; it is desirable that the cloth have from 0.5 to 2% pickup of the silicone resin. Water-soluble zirconium and/or tin salts are recommended as catalysts. About 4% tin, based on the silicone, is used. Melamine-formaldehyde resins may be used with the silicone emulsion. After the usual padding of the cloth with the emulsion, the cloth is dried and then cured at from 4 to 6 minutes at 150–155°C.

TEST METHODS

The ability of textile products to resist penetration and wetting (either spread of water over the surface or absorption) depends not only on the construction of the base fabric or yarn, the nature of the coating or repellent, and the method and efficiency of application, but also on "such 'external' factors as the amount of water in contact with the material, the time of contact, the temperature of the cloth and the water, the humidity-regain condition of the cloth, the force and energy with which the 'rain-drop' (or the alleged laboratory equivalent) strikes the fabric, the angle of strike, and the amount of abrasion, weathering, cleaning and other general service conditions to which the material is subjected" (26). Therefore, in addition to testing a new material for its water-resistant properties, the same tests should be performed after it has been subjected to appropriate service conditions, either actual or simulated in the laboratory. Water-repellent fabrics intended for rainwear should be evaluated also for air and water-vapor permeability since both are important comfort factors and do not necessarily correlate with each other (33).

Innumerable methods for evaluating the water-resistant characteristics and utility of textile products have been described (28,51). They vary greatly in procedure, complexity, and interpretation. Methods for fibers and yarns usually employ rate of sinking or absorbency principles. Those for fabrics may be arranged in four classes as follows: Class I: spray or sprinkling and drop tests to simulate the effect of rain in wetting and/or penetrating the fabric; Class II: hydrostatic pressure tests to simulate the effects of the pressure of water standing in a fabric, such as a tent roof, or in a bag or hose; Class III: immersion tests, with or without mechanical action, to check the

effectiveness of the water-repellent in reducing absorbency; and Class IV: surface tension methods, involving measurements of contact angle or some function of it, to evaluate the repellency or wettability of the surface.

Brief descriptions are given below of the present most commonly used tests for fabrics. For the most part, these have been fairly well standardized in the U.S. by the American Association of Textile Chemists and Colorists (A.A.T.C.C.), the American Society for Testing Materials (A.S.T.M.), and the branches of the Federal Government. Designations and references for such tests are given in Table II.

TABLE II. Methods for Evaluating Water-Resistant and Closely Related Properties of Textile Fabrics.

Test method	Test reference			
	A.A.T.C.C. (1)	A.S.T.M. (2,3,4)	Fed. Spec. CCC-T-191b (60)	Other
Class I:				
Spray test	22-52	D583-54	5526	
Rain test	35-52	D583-54	5524	
Drop penetration test		D583-54	5520	
Bundesmann water-repellency test				(55)
Class II:				
Hydrostatic				
Suter or A.A.T.C.C.-test	18-52	D583-54	5514 and 5516	
High range (Mullin)			5512	
Class III:				
Dynamic absorption	70-52	D583-54	5500	
Static absorption	21-52	D583-54	5502	
Class IV:				
Contact angle				(62)
Rolling drop				(49)
Supplementary tests:				
Air permeability				
N.B.S-Frazier apparatus		D737-46	5450	
N.B.S-Frazier apparatus or Permeometer		D737-46		
Densometer			5502	
Water-vapor permeability		E96-53T		

Class I. The *spray test* is one of the most widely used and simplest to perform. It distinguishes between untreated and treated fabrics, but does not detect small differences in water repellency. Results are independent of fabric construction, for it is a measure of resistance to wetting only and not of resistance to penetration. Essentially, 250 ml. of water is sprayed on the test specimen which has been mounted on an embroidery hoop at a 45° angle in such a manner that the center of the specimen is 6 in. below the spray nozzle. The amount of wetting is determined by visual comparison with photographic standards.

The *A.A.T.C.C.-Slowinske raintester* simulates the effects of rainfalls of different intensities by control of the hydrostatic head acting on the spray. The amount of water penetrating the fabric within a specified time at any fixed head is found by determining the increase in weight of a blotter placed behind the fabric. From comparative data, a series of fabrics can be rated for resistance to penetration.

The *drop penetration tester* simulates the effect of heavy rain by successive drops falling from a 68-in. height and striking the fabric in the same spot. The amount of

water passing through the fabric in a fixed time is determined. This tester, which was developed for the United States Quartermaster Corps, provides a relatively severe test but one that has been found especially useful for predicting order of protection in heavy rains. The energy of the drops is approximately 10,000–15,000 ergs, whereas the energy of drops in a cloudburst is about 3000 ergs.

The *Bundesmann water-repellency tester* is little used in the U.S., but it is used in a standard method in Great Britain (55) and Germany. It deserves mention for it appears to imitate service conditions for rainwear better than any of the other tests described. The rubbing and flexing action on the inside of a garment during wear is simulated by the action of wiper arms rubbing on the underside of the test specimen while it rotates under the standard shower designed to imitate a heavy downpour. The amount of water passing through in a fixed period of time is measured and the amount absorbed by the fabric is determined by weighing.

Class II. With the *A.A.T.C.C.- and Suter-type hydrostatic pressure testers,* either the head required to cause penetration or the amount of water passing through in a given time at a fixed head is determined. This test is especially applicable to coated and to heavy, closely woven fabrics, such as ducks and canvas, which are to be used in contact with water. It is also very useful for detecting pinholes in coated fabrics and for studying the penetration behavior of untreated swelling-type fabrics. Results are largely dependent on the pore sizes in the cloth. On water-repellent rainwear fabrics, test results do not necessarily correlate with behavior in use—for even though such fabrics permit passage of water under a hydrostatic head, they are highly resistant to wetting and to water transmission by capillarity.

The *Mullin-type bursting-strength tester* has been adapted for testing very heavy fabrics, including fire hose, for resistance to leakage under high pressures. For these tests, water is substituted for the usual glycerin and the test specimen replaces the rubber diaphragm.

Class III. The *dynamic absorption test* and the *static (immersion) absorption test* consist of tumbling (dynamic) or simply immersing (static) preweighed specimens in water for a fixed period of time and reweighing after the removal of the excess water. The percentage increase in weight indicates the efficiency of the water-repellent finish.

Class IV. *Surface tension* measurements are helpful in evaluating new water repellents but have not been proven practical for general use. Test procedures are variously described in the literature but have not been standardized. Measurement of the contact angle is the most usual procedure (62), but more recently a surface-tension index or "rolling-drop" method has been developed by Schuyten, Weaver, and Reid (49). A series of known surface tensions is used to determine the surface tension of the solution necessary to cause wetting of the sample. This method has special advantage over the spray test in that it permits greater differentiation among different repellents or among different methods of application to a standard cloth.

Supplementary Tests. *Air permeability* is generally measured in terms of cubic feet of air per square foot of fabric at a pressure drop of 0.5 in. of water, using either the Frazier air-permeability apparatus, developed at the National Bureau of Standards, or the Gurley Permeometer. Tightly woven, lightweight, nonresilient fabrics below the capacities of these instruments can be tested by the falling-cylinder method, using the Gurley Densometer. With this instrument, the time required for a known volume of air to be forced through the fabric under a continually falling pressure is measured.

Water-vapor permeability is a measure of the ability of the fabric to permit transfer

of sensible and insensible perspiration from the body to the surrounding atmosphere. Either of two general principles can be employed for this test, namely: determination of (*1*) the rate at which moisture evaporates from a standard dish containing water and covered with the fabric or (*2*) the rate at which moisture is absorbed by a desiccant in the standard dish covered with the fabric (4).

Durability tests for resistance to laundering, dry cleaning, weather, flexing, etc., are conducted in accordance with conventional test methods. See *Detergency*; *Dry cleaning*; *Laundering*; *Textile testing*.

Paper

Waterproof Paper. Broadly speaking, the term "waterproof paper" is purely relative and includes any type of paper that has a high resistance to penetration of water in liquid form. In the paper industry, however, "waterproof paper" has a specialized meaning, as defined in A.S.T.M. D996–52T, Definitions Relating to Shipping Containers:

> "A flexible paper, laminated, coated, or infused to give water or water-vapor resistance, may be creped for added flexibility and/or reinforced with strands of sisal or other fiber or backed with fabric for added strength. Used as box, bag, crate, barrel, and case liners, and bale wrappers."

The term refers most usually to kraft papers that have been laminated, infused, or saturated with asphalt. It has been extended, however, to include papers used for the same purposes made by lamination with thermoplastic waterproof resins, in particular polyethylene. In two-ply and three-ply constructions, microcrystalline wax is frequently substituted for asphalt. Both wax and resin laminants have certain advantages over asphalt in that they are more resistant to delamination, bleeding, and embrittlement at low temperatures. Some resins have the further advantage of permitting heat sealing (36).

In addition to the uses mentioned in the definition above, waterproof papers serve as water and vapor barriers in roofing materials, temporary tarpaulins, covers for concrete during curing, linings for freight cars and trucks, covers and shrouds for goods and machinery in transit, and interior wraps especially for export shipments. General requirements and test methods for papers of this type are covered in Federal Specification UU-P-271b, "Paper, wrapping, waterproofed kraft" and in Joint Army and Navy Specification JAN-P-125; "Packaging and Packing for Overseas Shipment—Barrier-materials, water-proof, flexible." Trials under service conditions are recommended when selecting papers for specific end uses.

"Waterproof paper" should not be confused with "moistureproof paper," designed to be resistant to water vapor; nor with "wet-strength paper," which retains its strength completely or partially after immersion in water. The latter has no special resistance to water penetration in either liquid or vapor form unless it has been coated or laminated to other components that impart water resistance. Wet-strength paper owes this characteristic to treatment of the stock with special resins, in particular melamine formaldehyde.

Water-resistant Papers. There are many kinds of papers that depend, in some degree, on water resistance for their utility; in fact, even writing and printing papers must have some degree of water resistance, imparted by rosin-sizing treatment, for, otherwise, they would absorb ink like a blotter. Many of the more resistant types are found in paper and paperboard products used for packaging materials and dispensing

foods and drinks. Common examples are butcher's wrapping paper; household waxed paper; glassine; butter, milk, and ice cream cartons; drinking cups; soufflé cups; and straws. Other much-used water-resistant papers are agricultural papers, such as plant protectors, celery-bleaching paper, and mulch paper; adhesive tapes, artificial leather; and vulcanized fiber. The water-resistant properties are achieved by many kinds of treatments, such as waxing; coating with resins, asphalt, rubber latex, and plastics; laminating with plastic or metal foil; vulcanizing with zinc chloride; treating with silicone; and parchmentizing with sulfuric acid (see also *Paper coatings*) (38, 42,54,65).

Leather

Greases, alone and in combination with oils and waxes, have long been applied to leather to protect the fibers against damage by water and to improve water repellency. For effective waterproofing, however, large amounts of grease (more than 50% by weight) are required, resulting in a slab of grease held together by leather (64). Consequently, the pores of the leather are largely filled so that the permeability to water vapor is extremely small and the leather is uncomfortable when worn. Furthermore, since the fats and greases tend to work out of the leather during flexing or on repeated wetting and drying, the waterproofing effect is usually temporary so that frequent reapplication of the treatment is necessary.

Impregnation of leather with degraded natural rubber reduces the water absorption and transmission of leather about 50%, but does not seriously impair its water-vapor permeability (25,41). Sole leather can also be waterproofed by incorporating vulcanized linseed oil. A laboratory method for impregnating vegetable-tanned crust leather and degreased chrome-retanned shoe upper leather uses polyisobutylene (Vistanex) which gives a water absorption about half that of the untreated leather, and an abrasion resistance of 100–160%. The wear was approximately 80% longer (40).

For both military and civilian wear, leather articles, such as shoes, gloves, and jackets, are often required to have high resistance to absorption and permeation by liquid water, but low resistance to the passage of water vapor. They are further required to have essentially the appearance, flexibility, and feel of the original leather. Under the auspices of the Office of the Quartermaster General, U.S. Army, a comprehensive investigation has been made of hydrophobic materials to replace the fats and greases used in present tannery practice "so as to increase the water repellency of the leathers and at the same time retain or enhance their existing desirable characteristics" (8,9). The most satisfactory materials found for gloves were the silicones, the methacrylates, and the Thiokol rubbers polymerized in the leather, and GR-S rubber and polybutadiene applied as polymers. The methacrylates and Thiokol rubbers polymerized within the leather were considered most satisfactory for boot and shoe upper leather. The report of this study by Cheronis (8) includes a bibliography of 322 references.

Silicone products designed for application to leather are being supplied in both solvent and emulsion forms. The leather is impregnated by dipping, drumming, or other mechanical means. The resultant surfaces are said to be durably water repellent and resistant to waterborne stains, and to retain air and water-vapor permeability characteristics as well as flexibility. This type of treatment is also applied to other leather products, such as upholstery, and sporting and mechanical goods.

A recent development is the "Bavon process," which provides for introducing alkylated succinic acids and derivatives of these acids into leather so as to produce a finish which is highly resistant to water penetration (69). The alkylated succinic acids have saturated or unsaturated alkyl groups substituted on the noncarboxylic carbon atoms of succinic acid. They may be applied in solution form by spraying, brushing, swabbing, and roller coating. Isopropyl alcohol, isopropyl alcohol–water mixtures, carbon tetrachloride, and mineral spirits, are among the solvents that may be used with these products. It is claimed that the treatment does not appreciably affect the original softness, flexibility, and porosity of the leather and that the water-resistant properties are durable under conditions of use involving bending and flexing.

Methods for testing the water resistance of leather and its products are included in the revised physical testing methods of the American Leather Chemists' Association (30) and in Federal Specification KK-L-311a(59). Resistance to water permeation is best tested under conditions simulating use. The Maeser dynamic water penetration machine, which imitates the effect of walking, has been used in the research program of the Quartermaster Corps to improve the water resistance of service shoes and combat boots (29,45). Cheronis (8,9) describes a "rain-brick" performance test for leather gloves. In the National Bureau of Standards test (59), the sample of leather is flexed during the test for resistance to penetration by water under atmospheric pressure. See also *Leather*; *Tanning materials*.

Concrete and Masonry

The term "waterproof" applied to concrete and masonry implies complete imperviousness to water and to water vapor, whether the liquid and vapor are under pressure or not. To be waterproof, protection with a waterproof barrier or coating, such as bituminous membrane (see "Waterproof paper," p. 975) is usually necessary because nearly all untreated concrete or masonry is more or less permeable to the passage of water and water vapor. The rate of capillary penetration of water under pressure through concrete is very small (39). Most difficulty occurs because of the leakage of water through openings larger than capillaries. Concrete or masonry which does not leak in this manner is considered "water resistant." If it neither leaks nor is capable of transmitting water by capillarity, it is described as "water-repellent." The latter, however, may be highly permeable to water vapor and may allow the transmission of water under pressure through its capillaries.

In order to eliminate and prevent unfair trade practices, the Federal Trade Commission promulgated "Trade Practice Rules for the Masonry Industry" in 1946. These relate among other things to the use of such significantly descriptive terms as "waterproof," "dampproof," "weatherproof," "watertight," and "vaporproof."

A number of standards giving requirements for asphalt, bituminous materials, and other products used in waterproofing and dampproofing concrete and masonry constructions have been established by the American Society for Testing Materials (5).

So called "waterproof" cements may contain a very small amount of a water repellent, such as a salt of a fatty acid. Mortar and concrete made from these cements may be water repellent but are not waterproof in the full sense of the term. "Pore fillers" such as magnesium fluosilicate are sometimes used. (See *Cement products*, Vol. 3, p. 493).

Above-grade walls are usually required only to be resistant to the leakage of wind-

driven rain, since the seepage by capillarity of rain water through such structures occurs very slowly and is usually of no practical importance. Water-repellent external surfaces are therefore preferable since they are highly water resistant but not waterproof. Waterproof coatings, such as oil-base paints, are vapor barriers and may be unsuitable because of possible condensation and trapping of moisture in the wall.

The National Bureau of Standards has done much work on the application of waterproofing materials to masonry. Results of a 13-year test on pore-sealers have been summarized by Kessler (27). Application of high-melting paraffin to heated masonry gave good results in sealing the pores (but not larger openings) against the capillary penetration of water. Tests of integral "waterproofings" for concrete against capillary penetration have been made by Jumper (24). The water permeability of walls built of masonry units was also studied by Fishburn (15). Later, when a number of surface coatings for permeable masonry walls were tested after application to small masonry wall specimens (17), it was found that the best results against leakage were usually obtained with a paint made of cement and water. Similar data on the effectiveness of cement-water paints were previously obtained by Copeland and Carlson (10). In their investigation, brush-applied coatings were found to be more water resistant than spray-applied coatings.

Silicone water repellents are sometimes used for above-grade constructions when only mild protection is required. They are said not to discolor masonry and to reduce staining caused by deposition of water-borne dirt. Their use permits passage of water vapor so that the structure can "breathe." As a result of reduced water absorption into the masonry, they probably lessen the possibility of frost damage and efflorescence.

Tests of silicone-treated walls have shown that the protection afforded against wind-driven rains is temporary for leakage occurred after a few hours exposure, the rate increasing with duration of test (16). Additional remedial treatments may therefore be needed—such as joint treatments or coatings of a portland cement grout or paint. Since these cementitious materials may not bond well to a water-repellent surface, they should be applied before the silicone water repellents are used.

For basements, tunnel constructions, building foundations, and such, it is usually necessary to make the structures waterproof or very highly water-resistant. For such purposes, waterproof barriers or coatings should be used to prevent or reduce the slow but constant seepage of moisture by capillarity as well as the leakage of water.

Bibliography

(1) A.A.T.C.C., "Water Resistance and Water Repellency of Fabrics," *1954 Yearbook*, Vol. 30, pp. 136–45.
(2) A.S.T.M., *Standards on Textile Materials (with Related Information)*, 1954, D583–54, pp. 215–26.
(3) A.S.T.M., *Standards on Textile Materials (with Related Information)*, 1953, D737–46, pp. 187–88.
(4) A.S.T.M., *Standards*, 1953 Supplement, Part VII, E96–53T, pp. 283–89.
(5) A.S.T.M., *Standards*, 1952, Part III, Cementitious Materials, Ceramics, Road and Waterproofing Materials, Thermal Insulation, Soils.
(6) Baxter, S., and Cassie, A. B. D., *J. Textile Inst.*, **36**, T67–90 (1945).
(7) *Chem. Week*, **74**, No. 10, 58–59 (1954).
(8) Cheronis, N. D., "The Development of Water Resistant Leathers," *U.S. Quartermaster Research Development Rept., Footwear Leather Ser.*, No. 8, 333 pp. (1954).
(9) Cheronis, N. D., *et al.*, *J. Am. Leather Chemists' Assoc.*, **44**, 282–308 (1949).
(10) Copeland, R. E., and Carlson, C. C., *Proc. Am. Concrete Inst.*, **36**, 169–92 (1940).

(11) Dahlen, M. A., and Pingree, R. A., "German Chemical Developments in Improving Water Resistance of Textiles," *Office Tech. Services Rept.*, **PB–1576**, 91 pp. (1945).
(12) Davis, F. V., *J. Soc. Dyers Colourists*, **63**, 260–63 (1947).
(13) Dean, J. D., "Preserving Cotton Fabrics in Outdoor Use," *U.S. Dept. Agr. Circ.*, **790**, 17 pp. (1948).
(14) Duggan, P., and Fortess, F., *Modern Textiles*, **34**, No. 3, 31, 60, 62, 64, 66 (1953).
(15) Fishburn, C. C., *U.S. Natl. Bur. Standards, Building Materials and Structure Rept.*, **BMS 82**, 37 pp. (1942).
(16) Fishburn, C. C., Private Communication, July 27, 1954.
(17) Fishburn, C. C., and Parsons, D. E., *U.S. Natl. Bur. Standards, Building Materials and Structure Rept.*, **BMS 95**, 37 pp. (1943).
(18) Gibson, C. E., and Dennett, F. L., *Am. Dyestuff Reptr.*, **42**, P275–78 (1953).
(19) Goldthwait, C. F., and Smith, H. O., *Textile World*, **95**, No. 7, 105, 107, 196, 198 (1945).
(20) Hamalainen, C., Reid, J. D., and Berard, W. N., *Am. Dyestuff Reptr.*, **43**, 453–57 (1954).
(21) Harding, T. R., *J. Textile Inst.*, **42**, P691–P702 (1951).
(22) Horigan, F. D., and Sage, C. R., "A Literature Survey on Waterproofing and Water-Repellency of Textiles," *U.S. Quartermaster Corps. Tech. Libr. Bibliog. Ser.*, **2**, 81 pp. (1947).
(23) Iler, R. K., *Ind. Eng. Chem.*, **46**, 766–69 (1954).
(24) Jumper, C. H., *Bur. Standards J. Research*, **7**, 1147–77 (1931).
(25) Kanagy, J. R., and Vickers, R. A., III, *J. Am. Leather Chemists' Assoc.*, **45**, 211–42 (1950).
(26) Kaswell, E. R., "Water Repellency and Water Resistance," in Kaswell, *Textile Fibers, Yarns and Fabrics*, Reinhold, N.Y., 1953, pp. 236–55.
(27) Kessler, D. F., *J. Research Natl. Bur. Standards*, **14**, 317–43 (1935).
(28) Klingelhöfer, A., Mendrzyk, H., and Sommer, H., *Wiss. Abhandl. deut. Materialprüfungsanstalt*, No. 1, 1–41 (1940).
(29) Maeser, M., *J. Am. Leather Chemists' Assoc.*, **42**, 390–408 (1947).
(30) Maeser, M., *et al.*, *J. Am. Leather Chemists' Assoc.*, **48**, 218–26 (1953).
(31) Mandikos, G. J., *Am. Dyestuff Reptr.*, **37**, P587–95 (1948).
(32) Marsh, J. T., *An Introduction to Textile Finishing*, Chapman and Hall, London, 1947, pp. 457–91.
(33) Martin, G. E., Sell, H. S., and Habeck, B. W., *Rubber Age*, **66**, 409–15 (1950); *Textile Research J.*, **20**, 123–32 (1950).
(34) Mayer, M., Jr., Kyame, G. J., and Brown, J. J., *Textile World*, **102**, No. 7, 114–15, 210 (1952).
(35) Mierzinski, S., *The Waterproofing of Fabrics*, Van Nostrand, N.Y., 1922, 144 pp.
(36) *Modern Packaging Encyclopedia*, latest ed., Packaging Catalog Corp., N.Y.
(37) Morel, A., *Industrie textile*, **67**, 450–51 (1950).
(38) Mosher, R. H., *Specialty Papers; Their Properties and Applications*, Chemical Pub. Co., N.Y., 1950, 520 pp.
(39) Norton, P. T., and Pletta, D. H., *Proc. Am. Concrete Inst.*, **27**, 1093–132 (1931).
(40) Oehler, R., Dahl, S., and Kilduff, T. J., *J. Am. Leather Chemists' Assoc.*, **47**, 642–60 (1952).
(41) Oehler, R., Kilduff, T. J., and Dahl, S., *J. Am. Leather Chemists' Assoc.*, **45**, 349–77 (1950).
(42) *Paper Year Book*, Davidson Pub. Co., Chicago, Ill., 1953.
(43) Pearson, H. P., *Waterproofing Textile Fabrics*, Chemical Catalog Co., N.Y., 1924, pp. 27–31.
(44) Reid, J. D., and Goldthwait, C. F., "Crops in Peace and War," *U.S. Dept. Agr. Yearbook*, **1950–51**, pp. 411–18.
(45) Roddy, W. T., *J. Am. Leather Chemists' Assoc.*, **43**, 419–22 (1948).
(46) Rowen, J. W., and Gagliardi, D., *J. Research Natl. Bur. Standards*, **38**, 103–17 (1947).
(47) Schuyten, H. A., Reid, J. D., Weaver, J. W., and Frick, J. G., Jr., *Textile Research J.*, **18**, 396–415, 490–503 (1948).
(48) Schuyten, H. A., Weaver, J. W., Frick, J. G., Jr., and Reid, J. D., *Textile Research J.*, **22**, 424–32 (1952).
(49) Schuyten, H. A., Weaver, J. W., and Reid, J. D., *Am. Dyestuff Reptr.*, **38**, 364–66 (1949).
(50) Shapiro, L., in Mauersberger, *American Handbook of Synthetic Textiles*, Textile Book Pub. Co., a division of Interscience, N.Y.-London, 1952, pp. 965–70.
(51) Slowinske, G. A., and Pope, A. G., *Am. Dyestuff Reptr.*, **36**, P108–21 (1947).
(52) Sookne, A. M., "The Problem of Water-Repellent Fabrics," in Textile Research Inst., *Symposium on the Functional Properties of Clothing Fabrics*, N.Y., 1943, pp. 12–15 (see ref. 26, p. 254).
(53) Speer, R. J., and Carmody, D. R., *Ind. Eng. Chem.*, **42**, 251–53 (1950).

(54) Stephenson, J. N. (ed.) *Pulp and Paper Manufacture: Manufacture and Testing of Paper and Board*, McGraw-Hill, N.Y., 1953, Vol. III, 945 pp.
(55) "Textile Institute Tentative Specifications Nos. 7 and 8," *J. Textile Institute*, **38**, S1–14 (1947).
(56) U.S. Defense Dept. Mil. Spec., *Duck, Cotton; Fire-, Water-, Weather-, and Mildew Resistant*, **MIL-D-10860** (QMC) (January 22, 1951).
(57) U.S. Dept. Commerce, Commodity Standards Division, *Recommended Commercial Standard for Water Repellent Textile Fabrics for Outerwear Apparel (Exclusive of coated fabrics and fabrics containing 50 per cent or more of wool)*, Washington, D.C., November 22, 1950, 12 pp., Mimeographed.
(58) U.S. Dept. Commerce, Office Tech. Services, *Bibliography of Reports on Water Repellency and Waterproofing of Textiles*, **IB-151** (July 1950).
(59) U.S. Federal Supply Service, Federal Spec. *Leather; Methods of Sampling and Testing*, **KK-L-311a** (January 19, 1953).
(60) U.S. Federal Supply Service, "Textile Test Methods," Federal Specification No. CCC-T-191b. U.S. Govt. Printing Office, Washington, D.C., May 15, 1951.
(61) U.S. Federal Trade Commission, *Proposed Trade Practice Rules Respecting Use of "Waterproof," "Rainproof," "Water Resistant," and Similar Designations as Descriptive of Outerwear, Fabrics for Outerwear, and Compounds or Treatments Therefor*, U.S. Govt. Printing Office, Supt. of Documents, Washington, D.C., April 21, 1953, 15 pp.
(62) Wakeham, H., Strickland, W. B., and Skau, E. L., *Am. Dyestuff Reptr.*, **34**, 178–82 (1945).
(63) Weaver, J. W., Schuyten, H. A., Frick, J. G., Jr., and Reid, J. D., *J. Org. Chem.*, **16**, 1111–16 (1951).
(64) Weir, C. E., Carter, J., Newman, S. B., and Kanagy, J. R., *J. Am. Leather Chemists' Assoc.*, **43**, 69–95 (1948).
(65) West, C. J., *Pulp and Paper Manufacture; Bibliography and United States Patents*. Technical Association of the Pulp and Paper Industry, N.Y., annual.
(66) Brit. Pat. 466,817 (June 7, 1937), R. J. W. Reynolds, E. E. Walker, C. S. Woolvin, and Imperial Chemical Industries, Ltd.
(67) Brit. Pat. 475,170 (Nov. 15, 1937), A. W. Baldwin, E. E. Walker, and Imperial Chemical Industries, Ltd.
(68) Brit. Pat. 549,974 (Dec. 16, 1942), F. T. Peirce, British Cotton Industry Research Assoc., W. C. Gardiner, and F. Reddaway and Co.; U.S. Pat. 2,350,696 (June 6, 1944), F. T. Peirce and W. C. Gardiner (to British Cotton Industry Research Assoc. and F. Reddaway and Co.).
(69) Brit. Pat. 694,586 (July 22, 1953), G. H. von Fuchs; U.S. Pat. 2,693,996 (Nov. 9, 1954), G. H. von Fuchs.
(70) U.S. Pat. 1,536,254 (May 5, 1925), C. B. White (to F. S. Bennett, Inc.).
(71) U.S. Pat. 2,273,040 (Feb. 17, 1942), R. K. Iler (to Du Pont).
(72) U.S. Pat. 2,306,222 (Dec. 22, 1942), W. I. Patnode (to General Electric Co.).
(73) U.S. Pat. 2,405,988 (Aug. 20, 1946), A. J. Barry (to Dow Chemical Co.).
(74) U.S. Pat. 2,588,365 (March 11, 1952), F. L. Dennett (to Dow Corning Corp.).
(75) U.S. Pat. 2,612,482 (Sept. 30, 1952), T. J. Rasmussen (to General Electric Co.).

J. DAVID REID AND RUBY K. WORNER